# Comprendre l'infiniment grand:

## cosmology and large scales in the Universe


17-27 juillet 2017
Orsay - Palaiseau - Paris - Saclay

Rencontres
DE L'INFINIMENT
GRAND
à l'infiniment petit

2017 : Promotion Lise Meitner

Visites de labos, conférences, débats
Comprendre l'infiniment petit
Les noyaux et leurs interactions
Des particules aux étoiles jusqu'au cosmos
Mesurer l'infiniment petit, observer l'infiniment grand
Applications médicales
Maîtriser l'énergie
Enregistrer, analyser, découvrir

Niveau L3

Valeria Pettorino
CEA Paris Saclay, Department of Astrophysics

CosmoStat

20th July, 2017

# We will talk about...

Cosmological principle, isotropy and homogeneity

Distances: Hubble law and expansion of the Universe

Abundances of light elements

Background Cosmology in General Relativity

Supernovae and Cosmic acceleration

Cosmic Microwave Background

Structure formation

The Dark Universe

# Some references

References:

Modern Cosmology, Dodelson

CMB physics and anisotropies: Hu & Dodelson 2002, Wayne Hu website, WMAP website: http://map.gsfc.nasa.gov/universe/

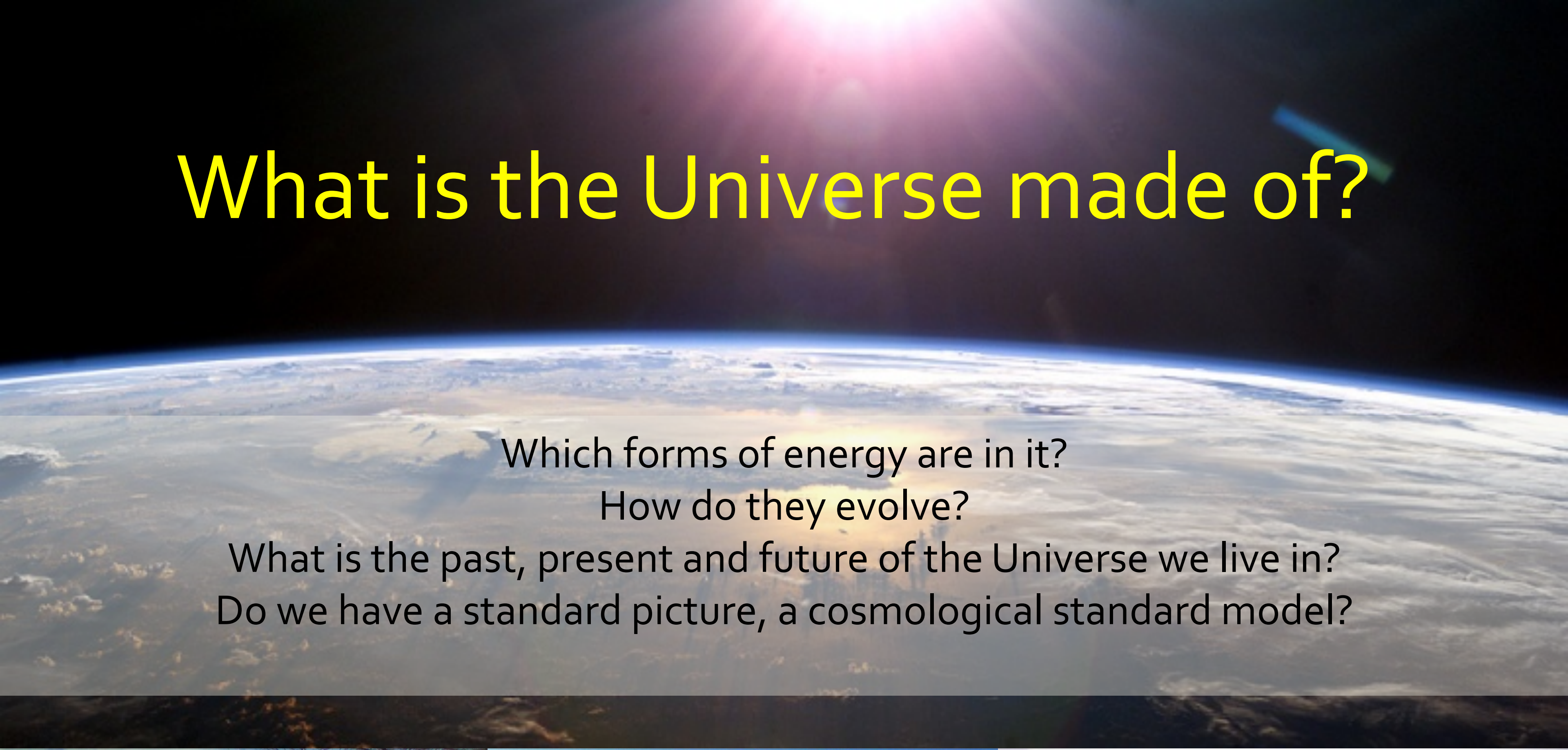
Dark Energy (Amendola & Tsujikawa)

Experiments: lambda.gfsc.nasa.gov

And references within the slides, which include work from several authors: L. Amendola, W. Hu, V. Springel, S. Dodelson, M. White, D. Weinberg, …

Distances: https://cosmology.carnegiescience.edu/timeline
https://telescoper.wordpress.com/2012/09/15/hubble-versus-slipher/

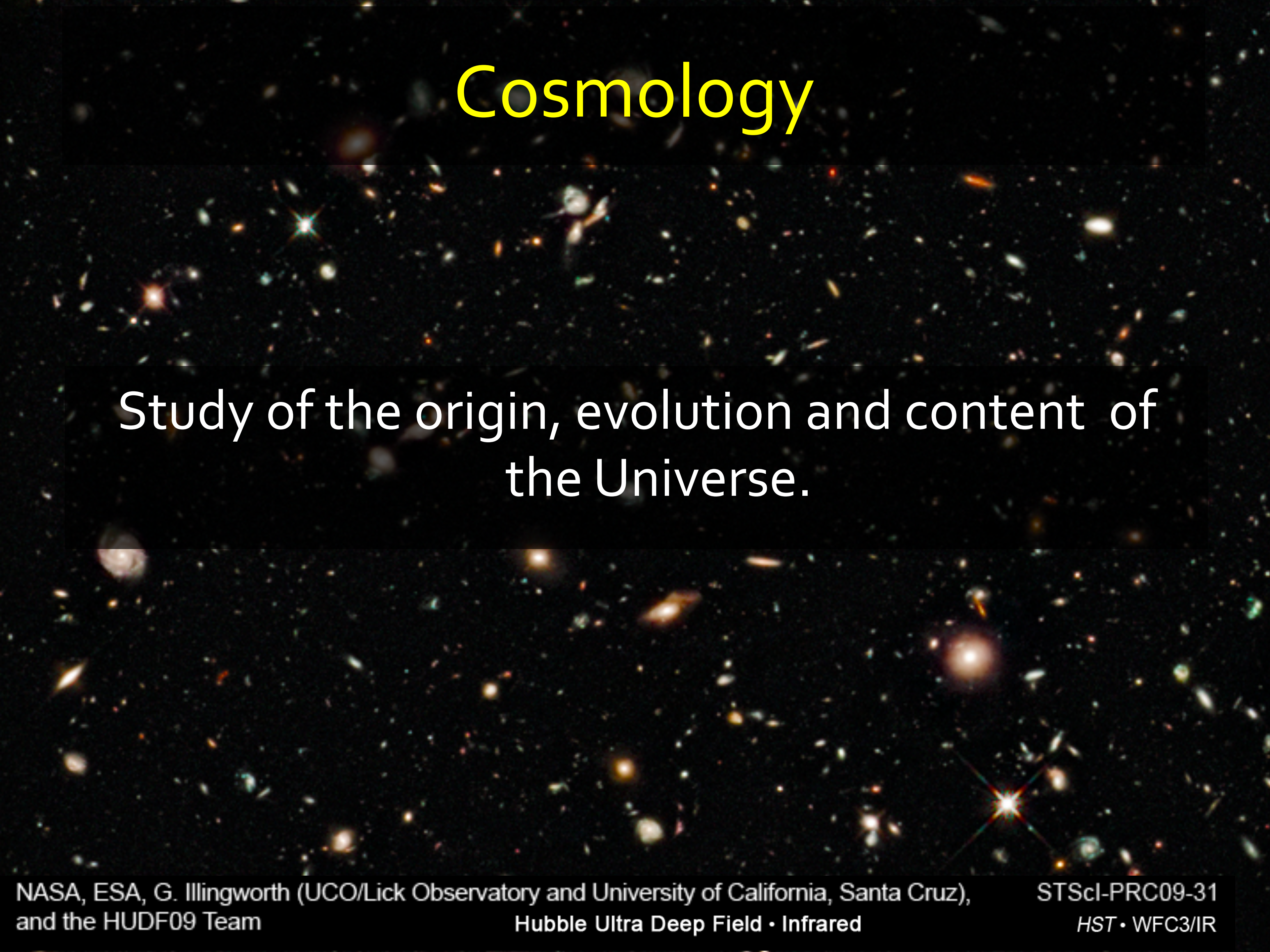
# What is the Universe made of?



Which forms of energy are in it?
How do they evolve?
What is the past, present and future of the Universe we live in?
Do we have a standard picture, a cosmological standard model?

# Cosmology

Study of the origin, evolution and content of the Universe.



NASA, ESA, G. Illingworth (UCO/Lick Observatory and University of California, Santa Cruz), and the HUDF09 Team

**Hubble Ultra Deep Field • Infrared**

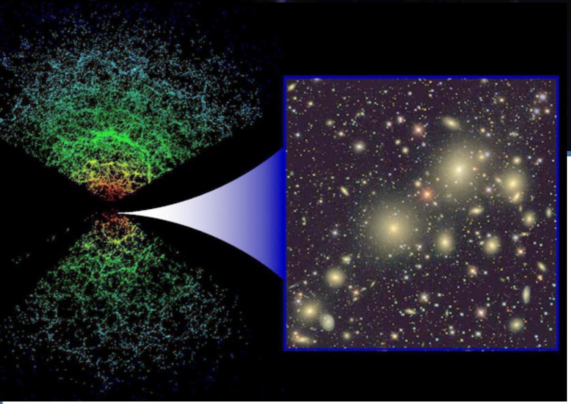
STScI-PRC09-31

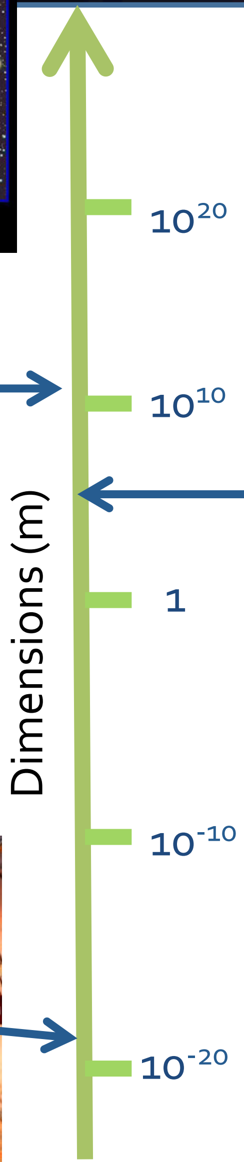
*HST* • WFC3/IR

# At which scales and distances are we looking at?

*"I apologize for the crudity of this presentation, but it's not on scale",*
*E.L.B. - Back to the future*

# Very different scales

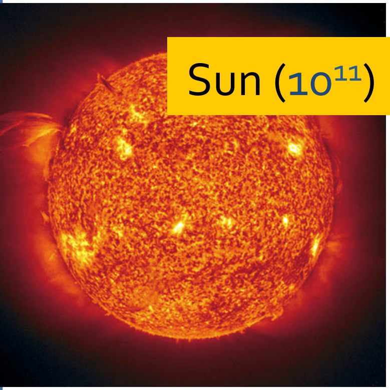




Cosmology ($10^{26}$)

Galaxies ($10^{20}$)

Astrophysics

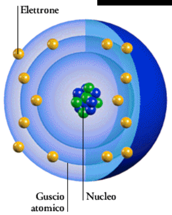


Sun ($10^{11}$)

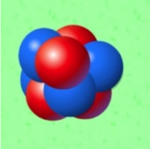
Earth ($10^{6}$)

Human beings

Chemistry



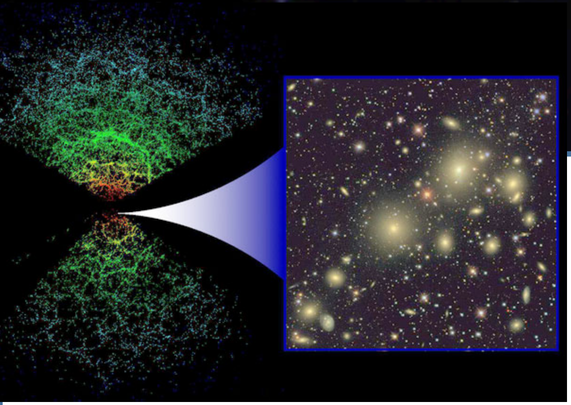
Atomic Physics ($10^{-10}$)



Nuclear Physics ($10^{-15}$)

LHC and particle physics ($10^{-19}$)

# Very different scales

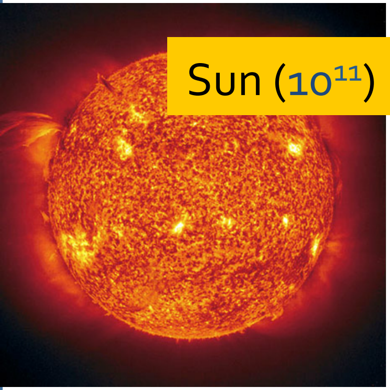


Cosmology ($10^{26}$)

Galaxies ($10^{20}$ = 30 kpc)

$10^{20}$

Astrophysics



Sun ($10^{11}$)

$10^{10}$

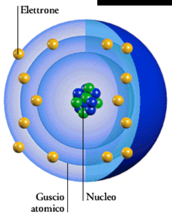
Earth ($10^{6}$)

Dimensions (m)

1

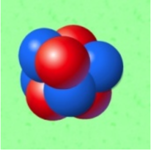
Human beings

Chemistry



$10^{-10}$

Atomic Physics ($10^{-10}$)



Nuclear Physics ($10^{-15}$)

$10^{-20}$

LHC and particle physics ($10^{-19}$)

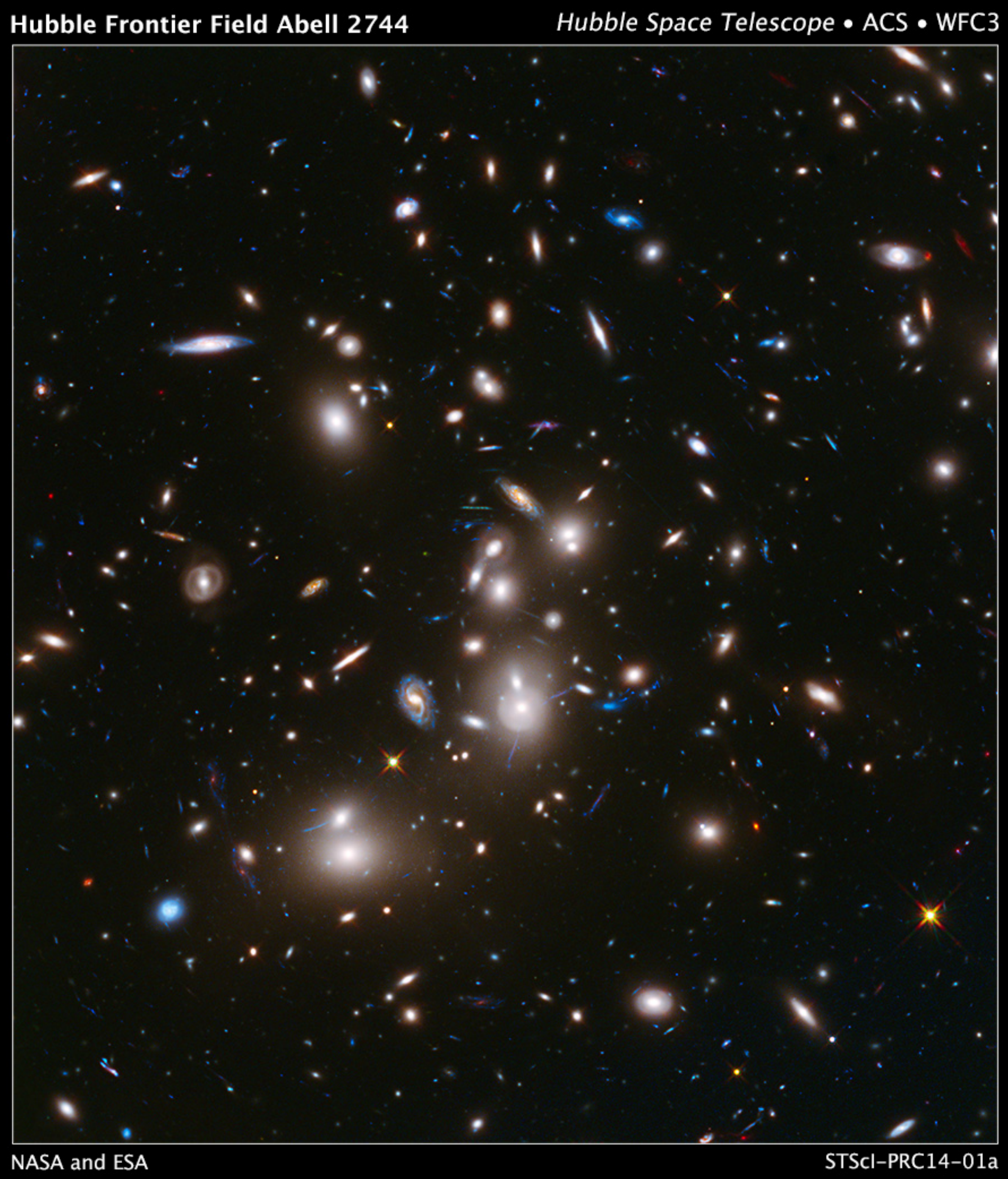
# A journey through the cosmos

Hubble Space Telescope

This long-exposure Hubble Space Telescope image of massive galaxy cluster Abell 2744 is the deepest ever made of any cluster of galaxies. It shows some of the faintest and youngest galaxies ever detected in space. Abell 2744, located in the constellation Sculptor […] contains several hundred galaxies as they looked 3.5 billion years ago. […] It acts as a gravitational lens to warp space and brighten and magnify images of nearly 3,000 distant background galaxies. The more distant galaxies appear as they did longer than 12 billion years ago. This image is part of […] an ambitious collaborative project among the NASA Great Observatories called The Frontier Fields.

Credit: NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI)

(7th January 2014)



‘The known Universe’
(developed by Americal Museum of Natural History)

Put things into perspective.

# What do we actually know?
# How is it like to work in cosmology?

In practice, what do cosmologists do?

# Not anymore a single astronomer


Bicep2 and SPT


Planck


Polarbear

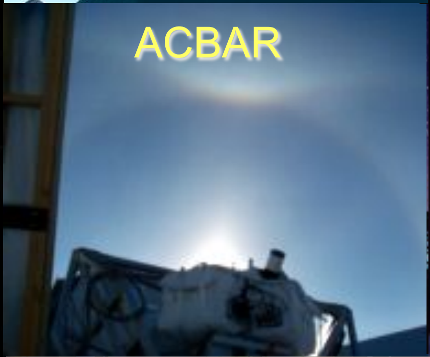

ACTpol


DASI


*Cosmic Background Imager*

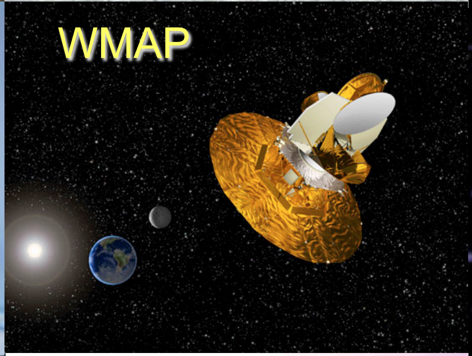

MAXIMA

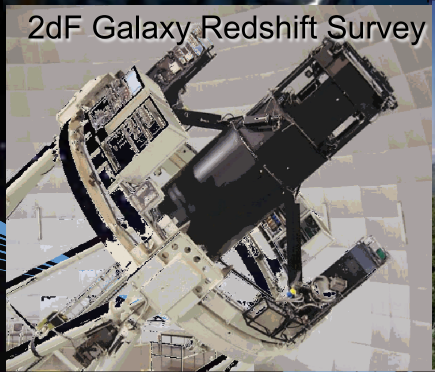

BOOMerang


ACBAR


COBE

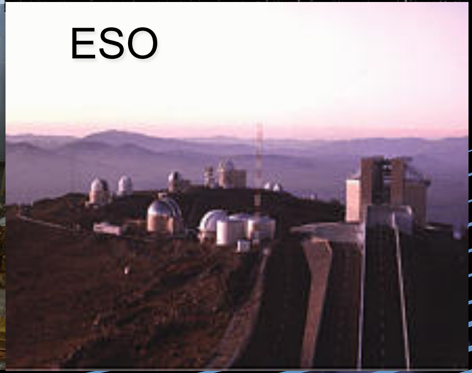

MSAM


WMAP

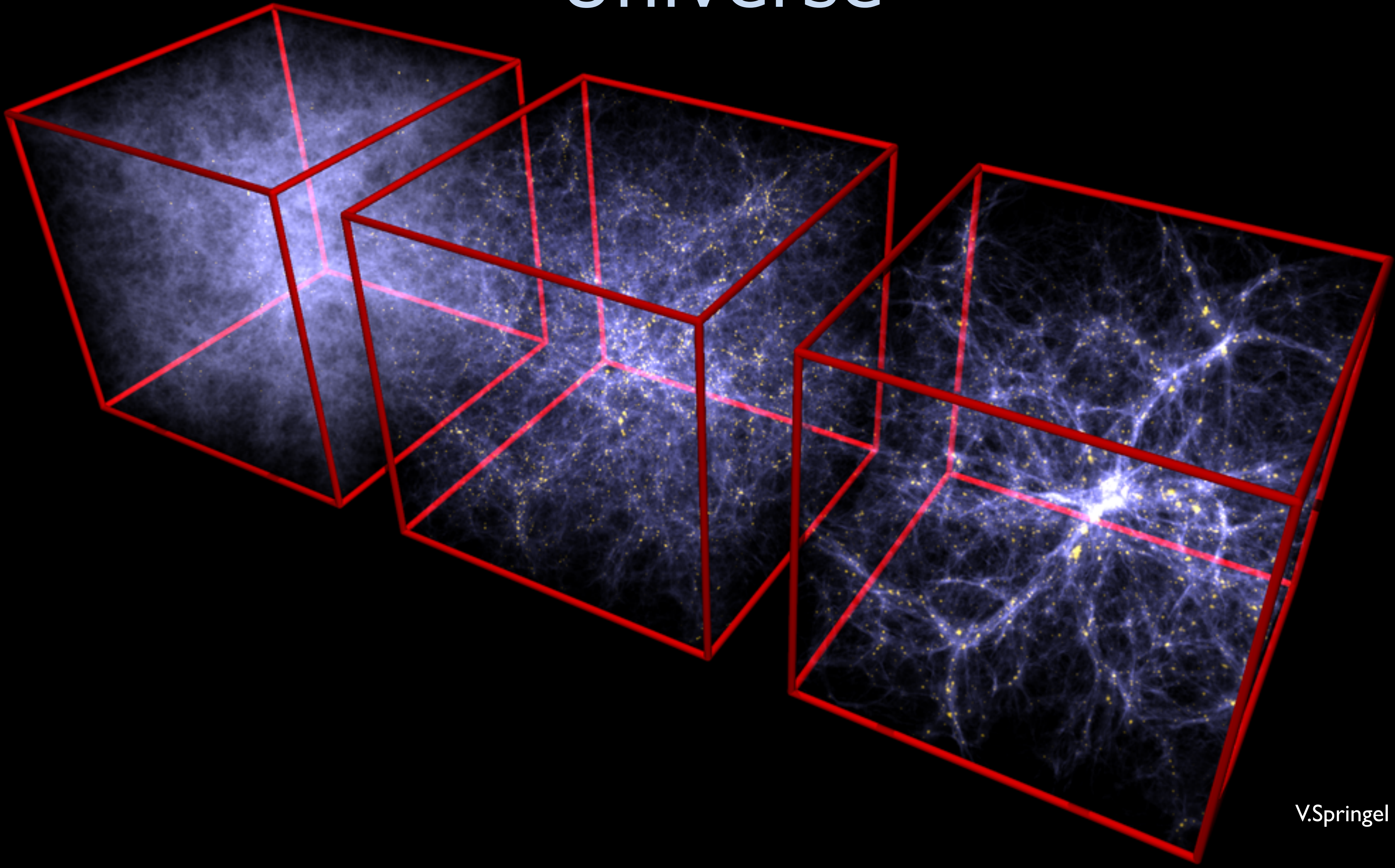

2dF Galaxy Redshift Survey


Sloan Digital Sky Survey


HST


ESO

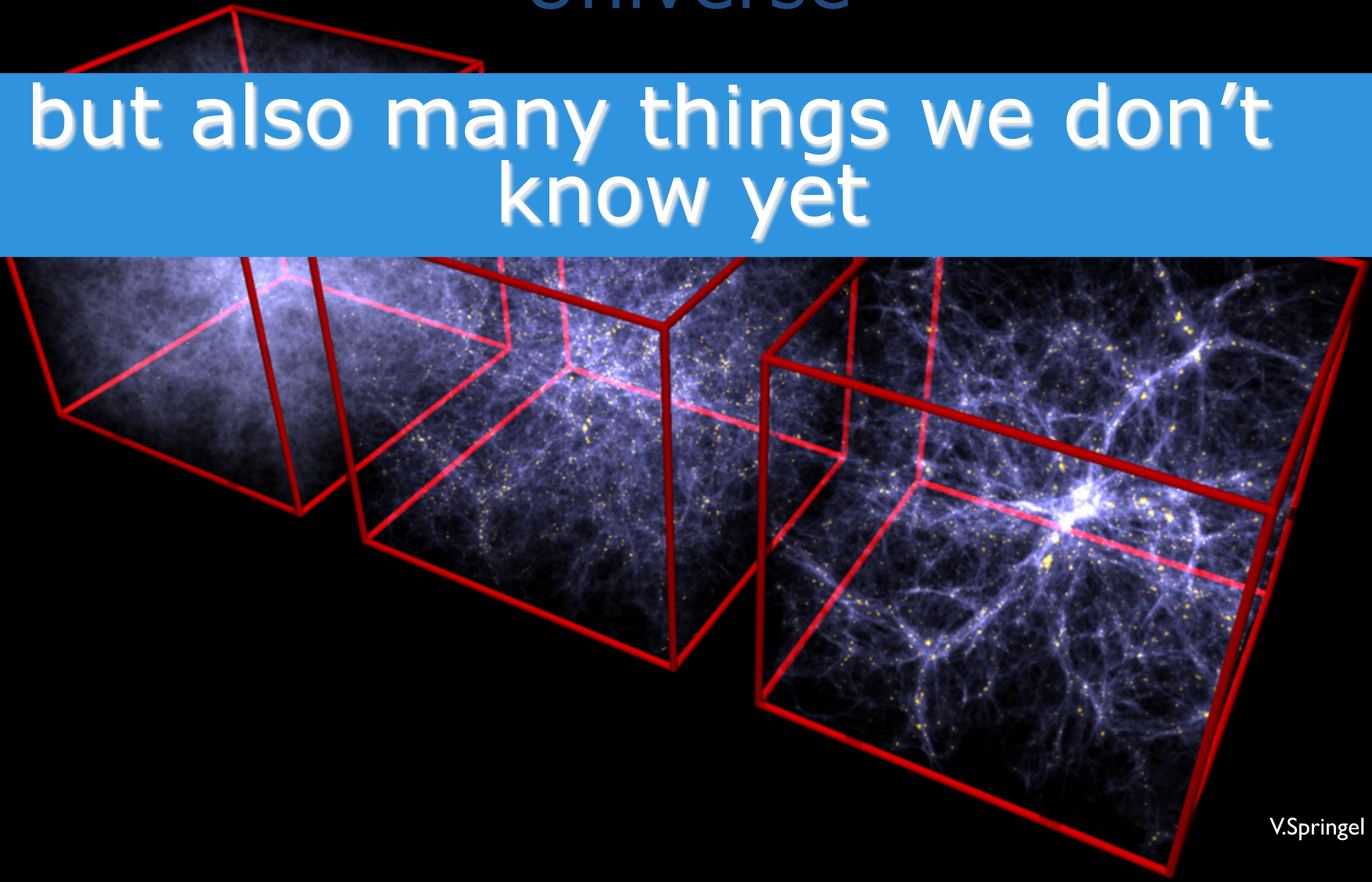
# We know a lot of things about the Universe



V.Springel

# We know a lot of things about the Universe

but also many things we don’t know yet



V.Springel

# Overview of standard cosmology

Cosmological principle, isotropy and homogeneity

Distances: Hubble law and expansion of the Universe

Abundances of light elements

Background Cosmology in General Relativity

Supernovae and Cosmic acceleration

Cosmic Microwave Background

Structure formation

The Dark Universe

# Overview of standard cosmology

Cosmological principle, isotropy and homogeneity

Distances: Hubble law and expansion of the Universe

Abundances of light elements

Background Cosmology in General Relativity

Supernovae and Cosmic acceleration

Cosmic Microwave Background

Structure formation

The Dark Universe

# Overview of standard cosmology

Cosmological principle, isotropy and homogeneity

Distances: Hubble law and expansion of the Universe

Abundances of light elements

Background Cosmology in General Relativity

Supernovae and Cosmic acceleration

Cosmic Microwave Background

Structure formation

The Dark Universe

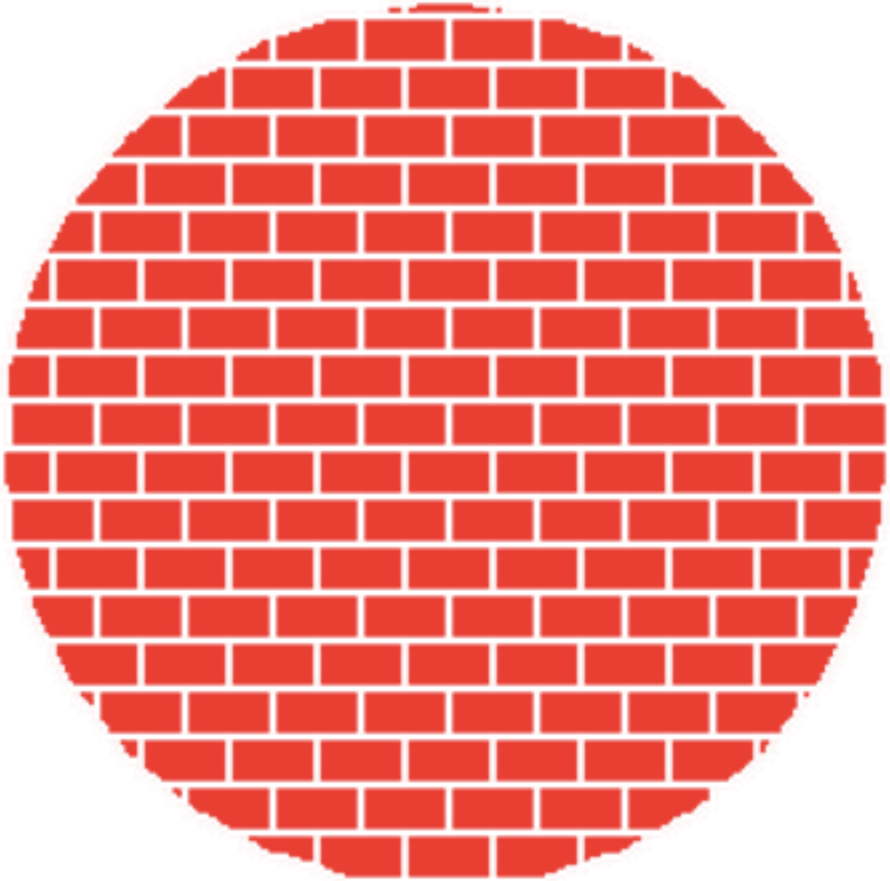
# The cosmological principle

We are not privileged observers, in a special position in the universe.

# The cosmological principle

We are not privileged observers, in a special position in the universe.

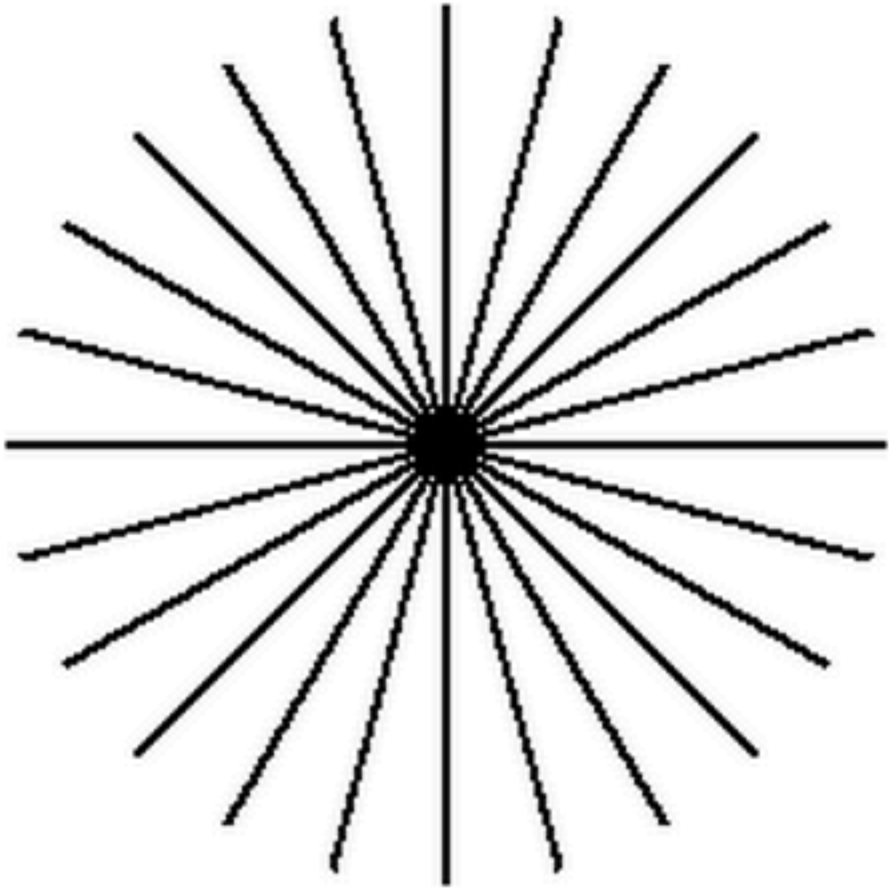
Homogeneity: at a given time, physical properties (ex. particle number density) are the same everywhere in space.



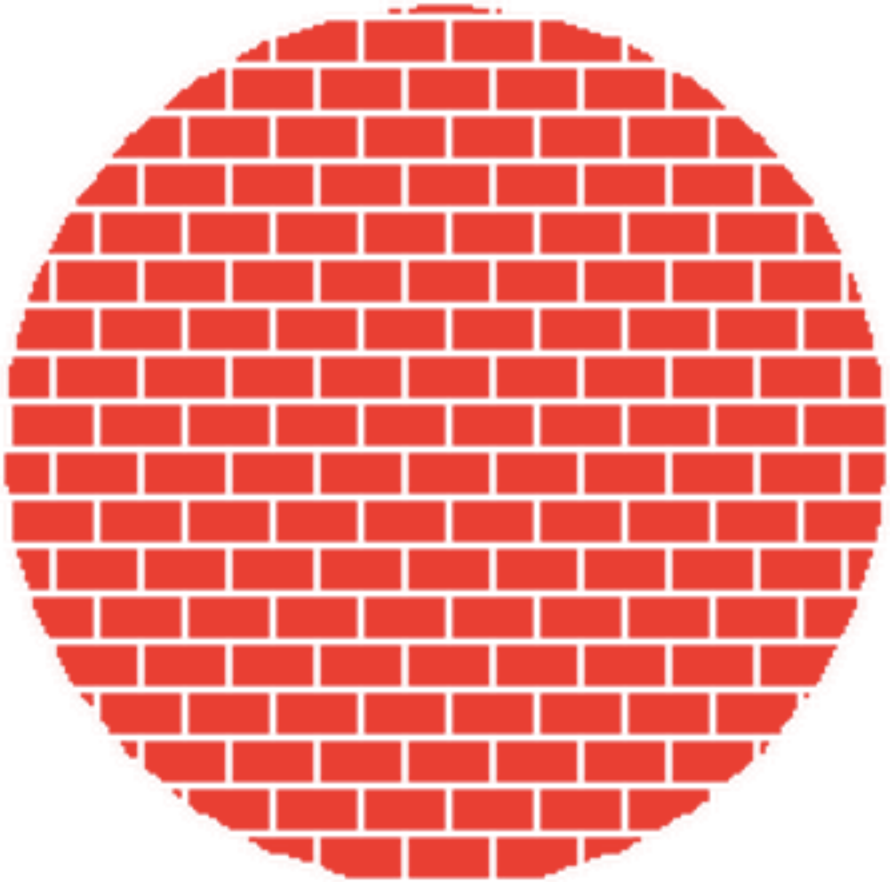
# The cosmological principle

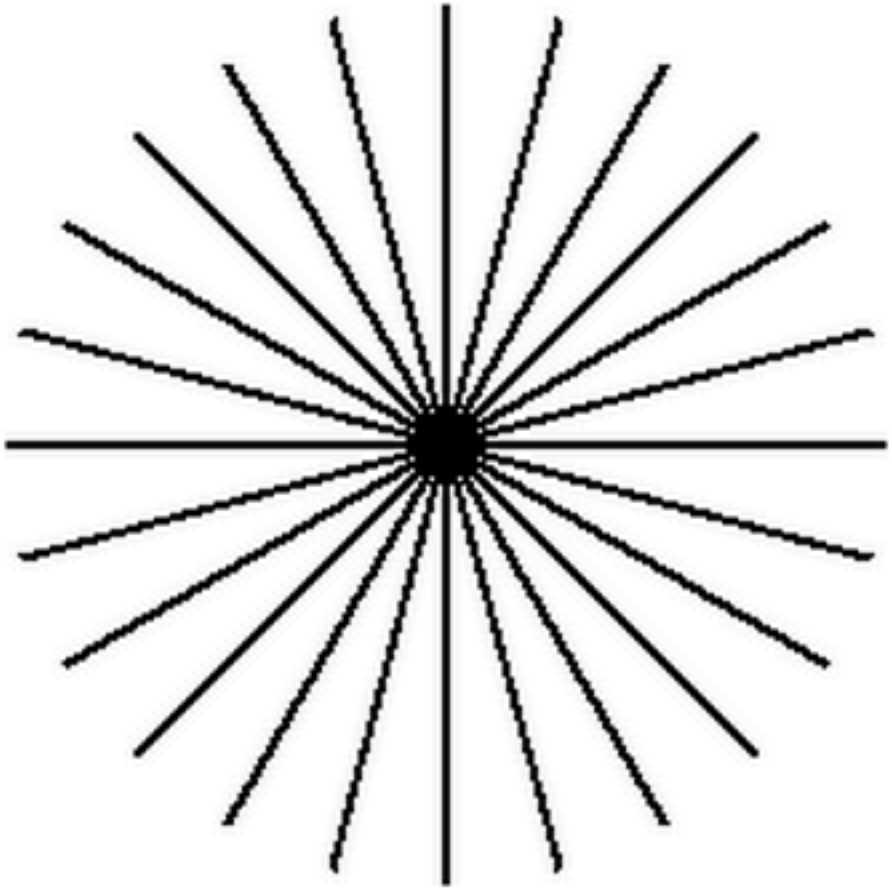
We are not privileged observers, in a special position in the universe.

Isotropy: physical quantities do not depend on the observation direction.



Two different concepts: but if it is isotropic to all observers, then it is also homogeneous.





**Picture from Ned Wright's Cosmology Tutorial**

# Overview of standard cosmology

Cosmological principle, isotropy and homogeneity

Distances: Hubble law and expansion of the Universe

Abundances of light elements

Background Cosmology in General Relativity

Supernovae and Cosmic acceleration

Cosmic Microwave Background

Structure formation

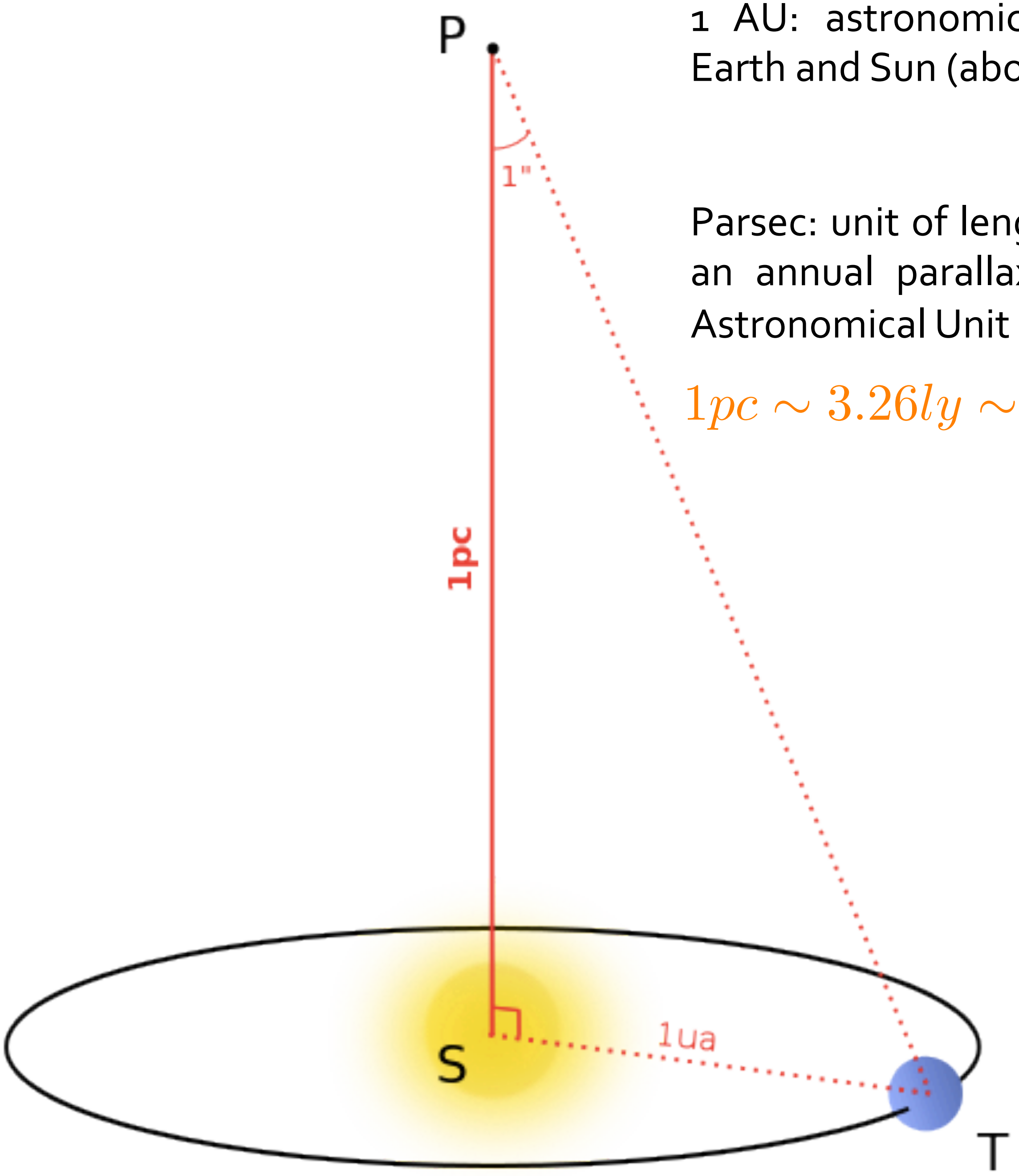
The Dark Universe

# Measuring distances

Distances are useful to measure intrinsic properties of objects in the Universe:

- Physical sizes of objects
- Masses of objects, given their orbital motion
- The laws that relate these properties
- Motion of stars through space
- Geometrical evolution of the Universe (expanding? Static? Distance is related to time)

Credit: R.Pogge, OSU



1 AU: astronomical unit, mean distance between Earth and Sun (about 150 billion m)

Parsec: unit of length, it is the distance of a star with an annual parallax of 1 arcsec, subtended by one Astronomical Unit (AU).

$$1pc \sim 3.26ly \sim 3.09 \times 10^{16}m \sim 206,000UA$$

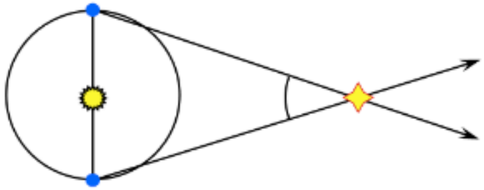
Stellar Parallax

Nearby stars appear to move with respect to more distant ones due to Earth motion around the Sun. Parallax angle.

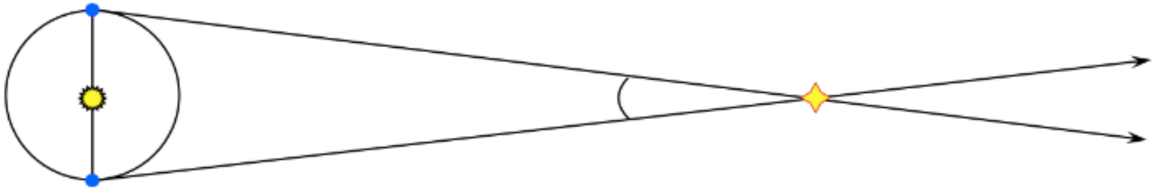
Parallax, first method to measure distances. The closer the star is, the larger is the parallax.

Used for distances up to 100 pc, corresponding to angles of 1/100 arcsec.

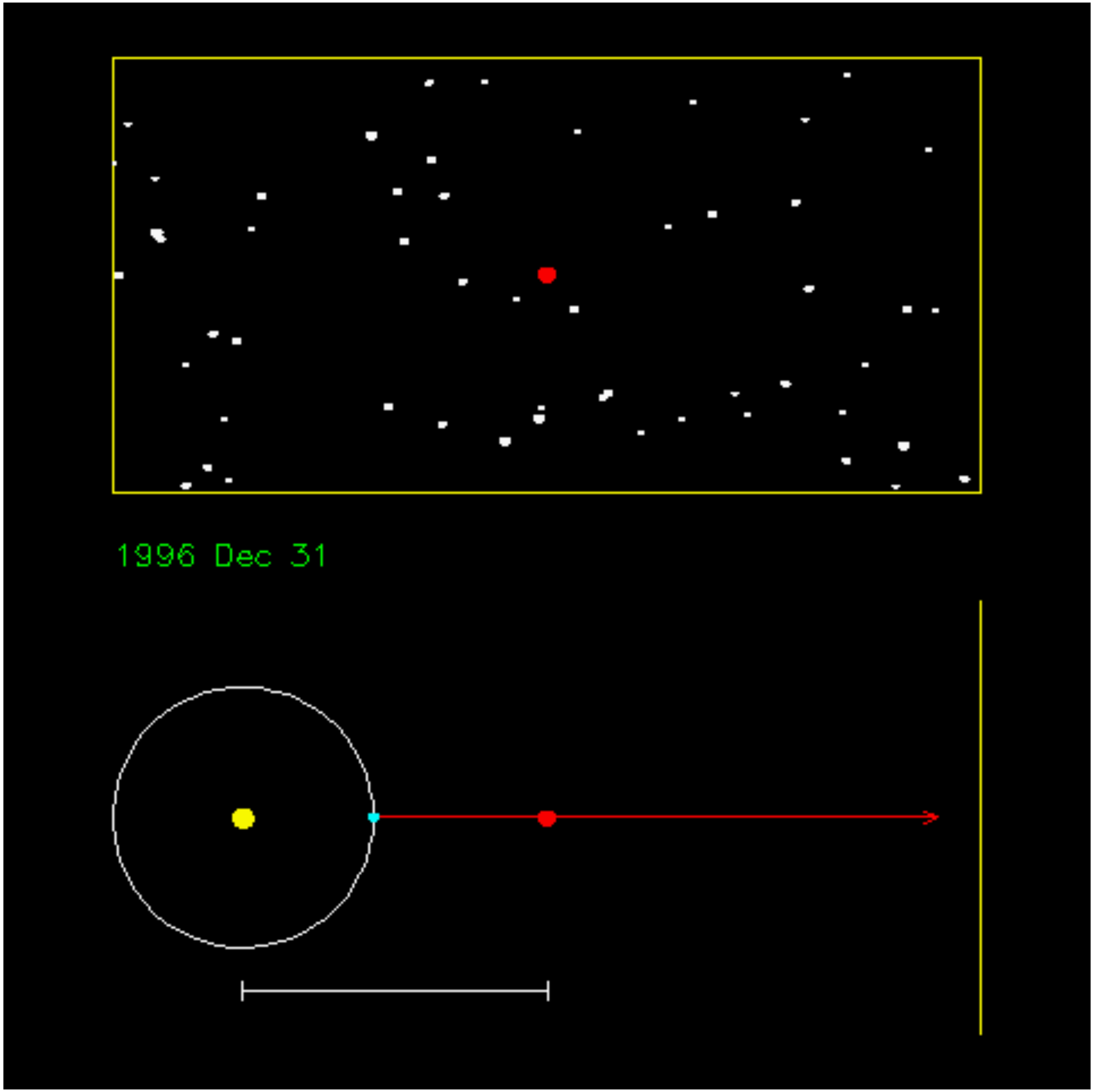
*Closer* stars have *larger* parallaxes:



*Distant* stars have *smaller* parallaxes:



Credit: R.Pogge, OSU



The top half of each frame shows the appearance of the sky as seen from the Earth (ignoring the Sun), and the bottom half shows a fixed view looking down from above onto the plane of the Earth's orbit around the Sun (the ecliptic).

The (red) star parallax motion is a reflection of Earth orbital motion.

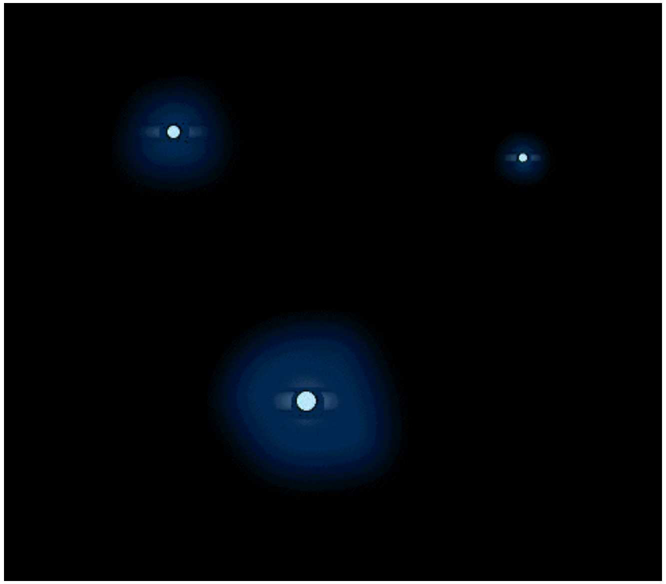
It looks like it is moving with respect to distant stars.

The furtherst the star is the smaller is its 'parallax' motion.
It can be used to obtain the distance.

Credit: R.Pogge, OSU

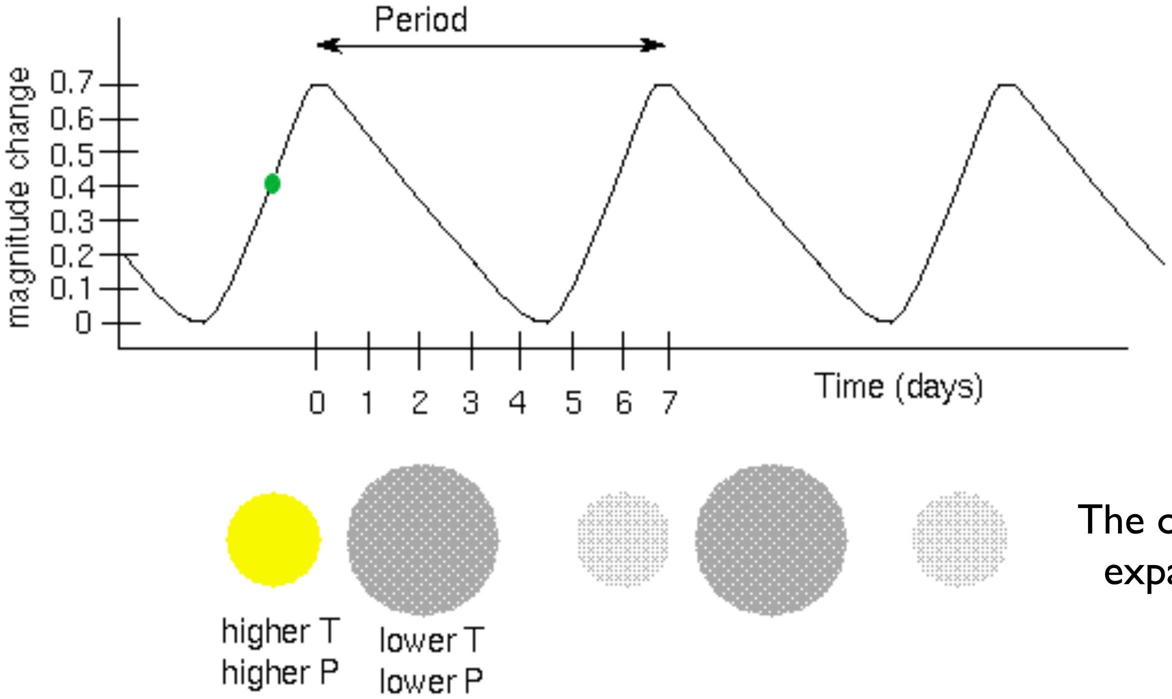
# Step by step through history

**1912: Henrietta Leavitt**, Harvard College Observatory: found the key to measure the distance to stars much further away than 100 light years. She identified more than 2400 variable stars (stars that change in brightness over a few hours/days/weeks) comparing photos taken at different times.
She looked for a relation between the brightness of a variable star and the length of its period.
Period of a variable star: the time to get brighter, dimmer and brighter again.
Difficult without knowing the intrinsic brightness.



Credit: https://cosmology.carnegiescience.edu/timeline/1929
http://www.astronomynotes.com/

# Step by step through history



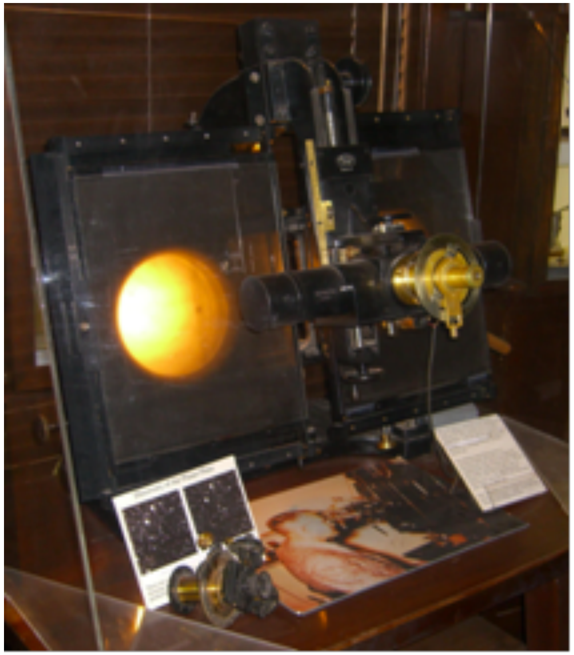
*Cepheid* variables: outward pressure (P) and inward gravity compression are out of sync, so star changes size and temperature: it **pulsates**. *RR-Lyrae* variables are smaller and have pulsation periods of less than 24 hours. Also, their light curve looks different from the Cepheid light curve.

The outer layers of the star periodically expanding and contracting cause this pulsation.

Credit: https://cosmology.carnegiescience.edu/timeline/1929
http://www.astronomynotes.com/

# Cepheids as a distance measurement

The Blink Comparator has been one of the most valuable instruments ever invented for the science of astronomy. Two photographic images of the same star field are placed on the left and right sides of the instrument. The observer looks in the middle and lines up the two plates. The comparator then switches back and forth between the two plates, so that a star that is changing in brightness would be seen to rapidly flash on and off, while all the other stars remain the same.



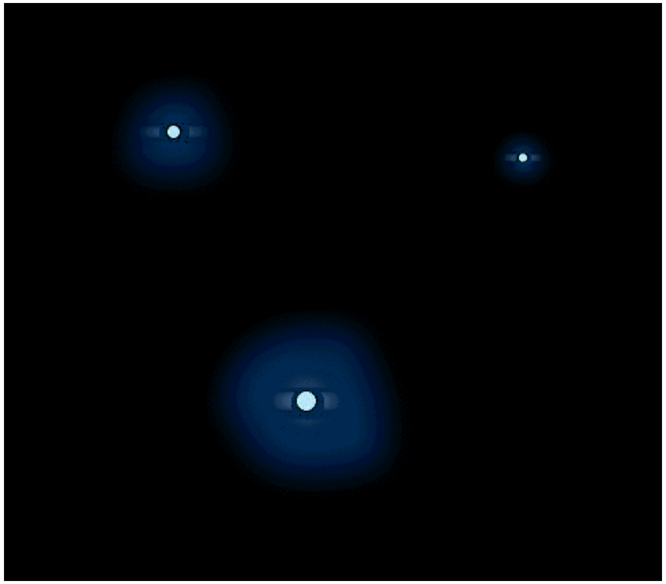
Blink comparator, Lowell Observatory. Image taken by Pretzelpaws

References: http://sci.esa.int/education
http://www.astronomynotes.com/
http://cosmology.carnegiescience.edu/timeline/1912/blink-comparator

# Step by step through history

She solved the problem by restricting to a particular kind of variable stars known as Cepheid variables, situated in the Small Magellanic Cloud (distant star cluster): all stars in the same cluster must be approximately the same distance from Earth. She identified 25 Cepheids in the cluster and plotted maximum brightness vs period. Brighter stars have longer periods.

This was the key to all subsequent discoveries related to measurements of distances and of the expansion of the universe.

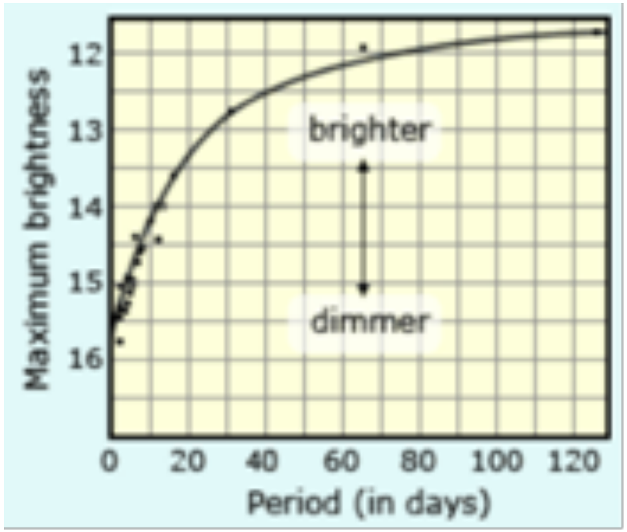


Leavitt did not know the distances to the Magellanic Clouds, so she could not tell what the actual value of the luminosity part of the relation was.

Credit: https://cosmology.carnegiescience.edu/timeline/1929
http://www.astronomynotes.com/

References: http://sci.esa.int/education
http://www.astronomynotes.com/

# Cepheids as a distance measurement

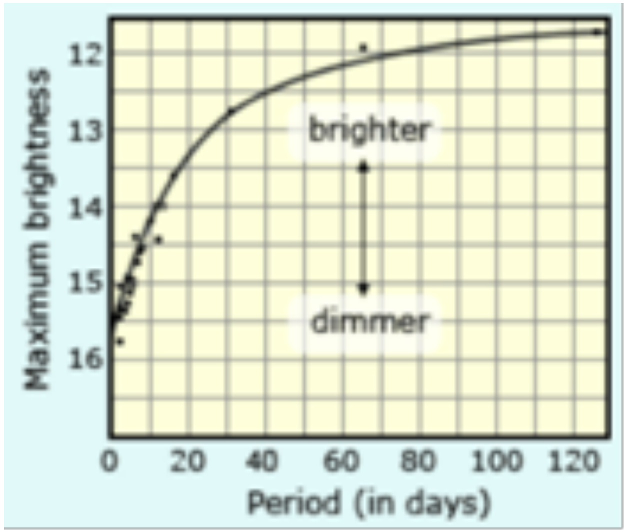


$$M = -2.78 \log (P) - 1.35$$

M = absolute magnitude
P = period (days)

References: http://sci.esa.int/education
http://www.astronomynotes.com/

# Cepheids as a distance measurement



$$M = -2.78 \log (P) - 1.35$$

M = absolute magnitude
P = period (days)

The procedure used later followed this set of steps:

- Measure the period of the star
- Use the Leavitt relation to determine the intrinsic brightness
- Measure how bright it actually appears
- Determine its distance (which can also be defined as the distance to the cluster galaxy in which it was found)

$$m - M = 5 \log d - 5$$

d = distance in parsec

# How it is actually still currently done

Galaxies with known distance in which there are Chepeids:
determine the absolute magnitude using Leavitt Law

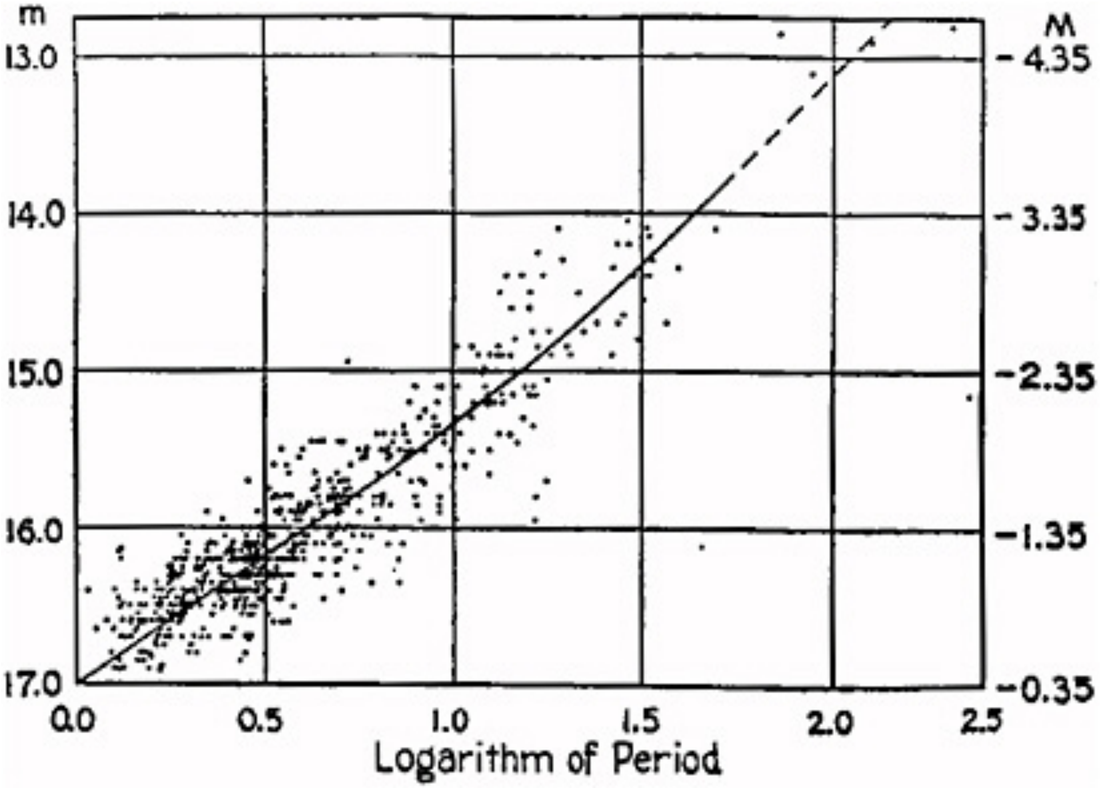
Assume the absolute magnitude is the same everywhere

Use the Leavitt Law in galaxies of which we don’t know the distance, which host both Chepeids and Supernovae to determine the distance

Use the relation between Supernova magnitude, distance and apparent magnitude to determine the expansion rate.

References: http://sci.esa.int/education
http://www.astronomynotes.com/

# Cepheids as a distance measurement



M = absolute magnitude
m = apparent magnitude
P = period (days)

# Step by step through history

1912: Vesto Slipher obtained the first radial velocity of a spiral nebula (Andromeda galaxy) followed by many other measurements, establishing that recession velocities are a general property of spiral nebulae. The most distant ones were all showing redshift (velocity recession away from the observer). He was very careful, serious and conservative and wondered about systematics or 'new physics'. This was then crucial when combined with Hubble distance measurements.

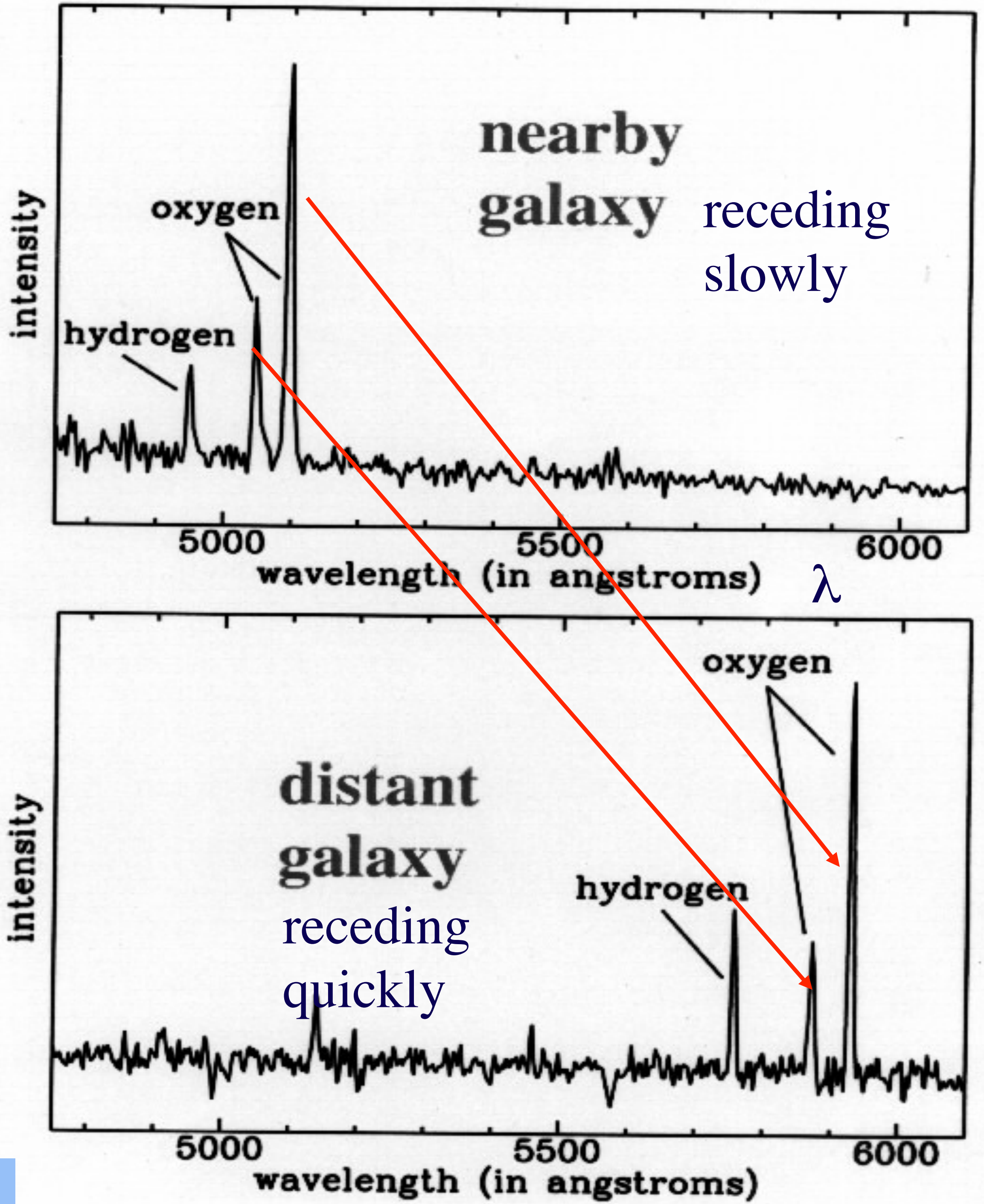
**Vesto Melvin Slipher**
**1875-1969**

Credit: [1] https://cosmology.carnegiescience.edu/timeline/1929
[2]: https://telescoper.wordpress.com/2012/09/15/hubble-versus-slipher/

`Doppler'
shift
of Galaxy
Emission/Abs.
Lines

$v/c \approx z = \Delta\lambda/\lambda_0$

(for v/c << 1)



Courtesy of L.Amendola

# Step by step through history

1914-1919: Harlow Shapley studied large groups of ‘stars’ called globular clusters and identified Cepheid variable stars in one of the nearest one.
He used the luminosity-period relation discovered by H Leavitt. In order to determine the absolute distance, he calibrated on Cepheids in our own galaxy, for which distances could be determined using parallax.
60-inch telescope
Controversy about the location of globular clusters, whether they were in the Milky Way (Shapley) or that at least some of these nebulae were whole galaxies at much larger distances (Curtis). Debate in April 1920. The question was not solved there, but a few years later by Hubble.

Portrait of Harlow Shapley. Image courtesy of Harvard College Observatory

Credit: [1] https://cosmology.carnegiescience.edu/timeline/1929
[2]: https://telescoper.wordpress.com/2012/09/15/hubble-versus-slipher/

# Step by step through history

Edwin Hubble was hired to work at Mount Wilson Observatory in 1919 (part of the Observatories of the Carnegie Institution of Washington)

The most pressing question of the day concerned the nature of the cloudy patches called nebulae. Most of Hubble's colleagues at Mount Wilson thought they were all in the Milky Way

He provided convincing evidence that at least some of them were well beyond the Milky Way

Edwin Hubble observing. Image courtesy of the Observatories of the Carnegie Institution for Science

Credit: https://cosmology.carnegiescience.edu/timeline/1929

# Step by step through history

Arrived at Mt. Wilson soon after the 100-inch reflecting telescope was completed. Hubble took many photographs of the same set of spiral nebulae (now called galaxies). Multiple images were needed in order to identify changes over time. On October 4, 1923, while comparing a photograph that he had just taken of the Andromeda galaxy with photos taken on previous nights, Hubble identified a Cepheid variable star. Comparing its apparent brightness with its actual brightness Hubble determined that it was 900,000 light years away.

Since Harlow Shapley had previously measured the distance across the Milky Way to be about 100,000 light years, the new findings clearly indicated that the Andromeda galaxy was far beyond the Milky Way. Later investigators found that there were two types of Cepheid variable stars, Andromeda was actually twice as far away—approximately 2 million light years. In subsequent decades, distances were measured to many other galaxies. Today, galaxies that are billions of light years distant have been observed.

Edwin Hubble observing.
Image courtesy of the
Observatories of the Carnegie
Institution for Science

1927: Lemaitre derived a linear relation between velocity and distance (including a Hubble constant)

Credit: https://cosmology.carnegiescience.edu/timeline/1929

# Step by step through history

1929 paper by Hubble:
http://www.pnas.org/content/15/3/168.full.pdf+html

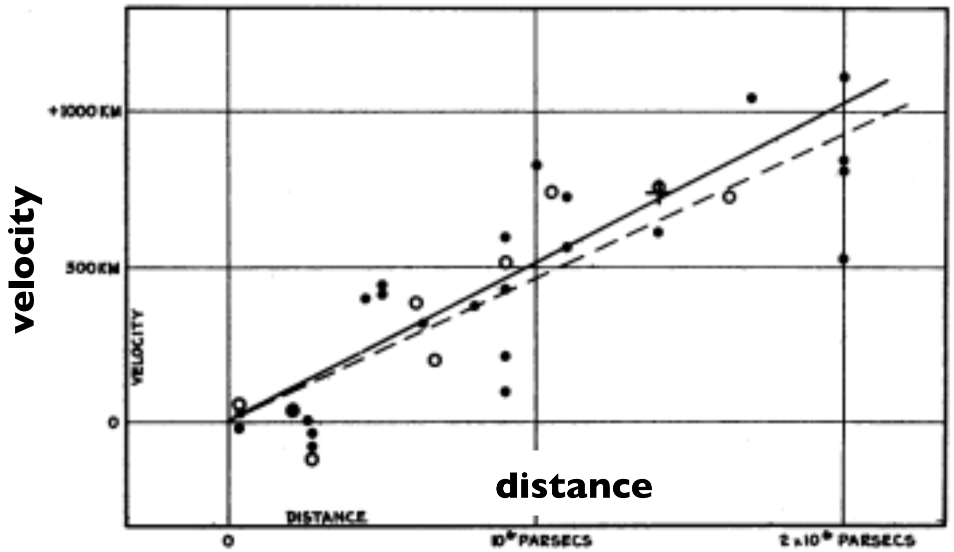


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

Hubble was aware that a decade earlier astronomer Vesto Slipher had measured the recession velocity of several galaxies (and used his data [2]), finding a few that were approaching our Milky Way and several that were moving away at very high speeds. Hubble measured the period of Cepheids and absolute luminosity (L) (from Leavitt relation). Then from the apparent brightness ($f=L/4\pi d^2$) he obtained the distances d.
He compared distances with the radial velocities v measured by Slipher, obtaining an empirical relation between the two.

In 1929 Hubble published a paper that would lead to the realization that the universe was expanding.

$v=H_0d$

Hubble's constant: $H_0=550$ km/s/Mpc (as measured at that time! Present measurements lead to about 70 km/s/Mpc)

Credit: [1] https://cosmology.carnegiescience.edu/timeline/1929
[2]: https://telescoper.wordpress.com/2012/09/15/hubble-versus-slipher/

# Age of the Universe

1929 paper by Hubble:
http://www.pnas.org/content/15/3/168.full.pdf+html

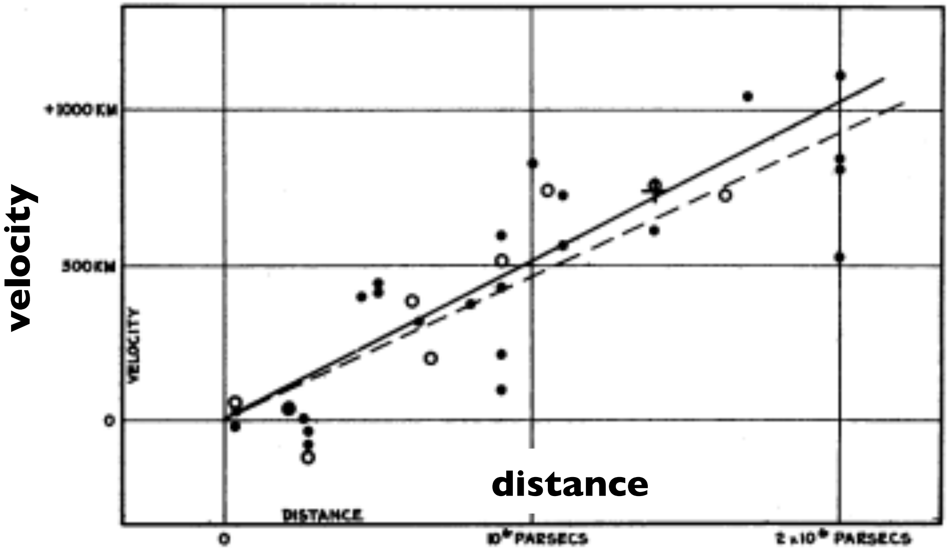
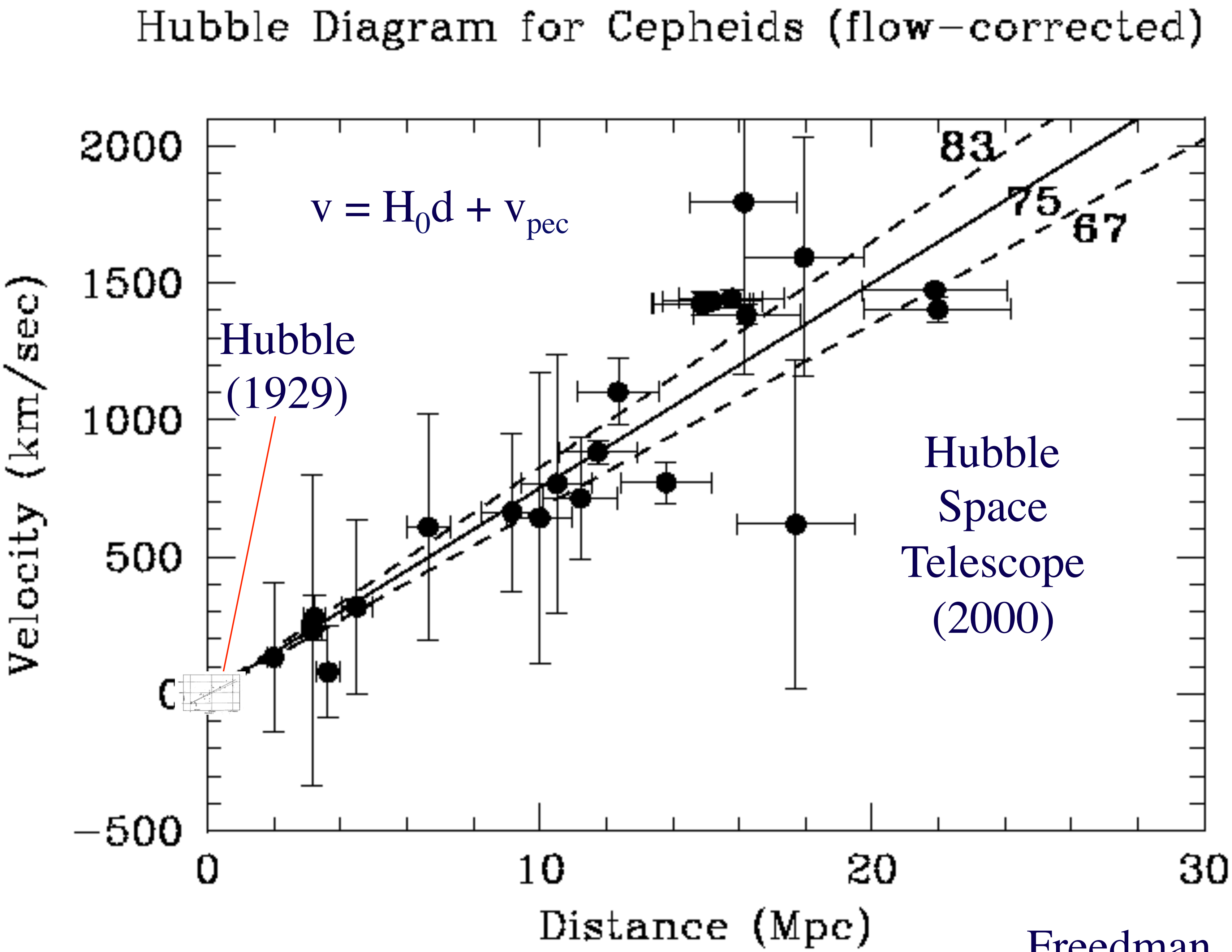


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

Discovery of the expanding universe was confirmed. By measuring the rate of expansion it was possible to determine the age of the universe by calculating when all the galaxies were in one place.

Credit: [1] https://cosmology.carnegiescience.edu/timeline/1929
[2]: https://telescoper.wordpress.com/2012/09/15/hubble-versus-slipher/



$v = H_0 d + v_{pec}$

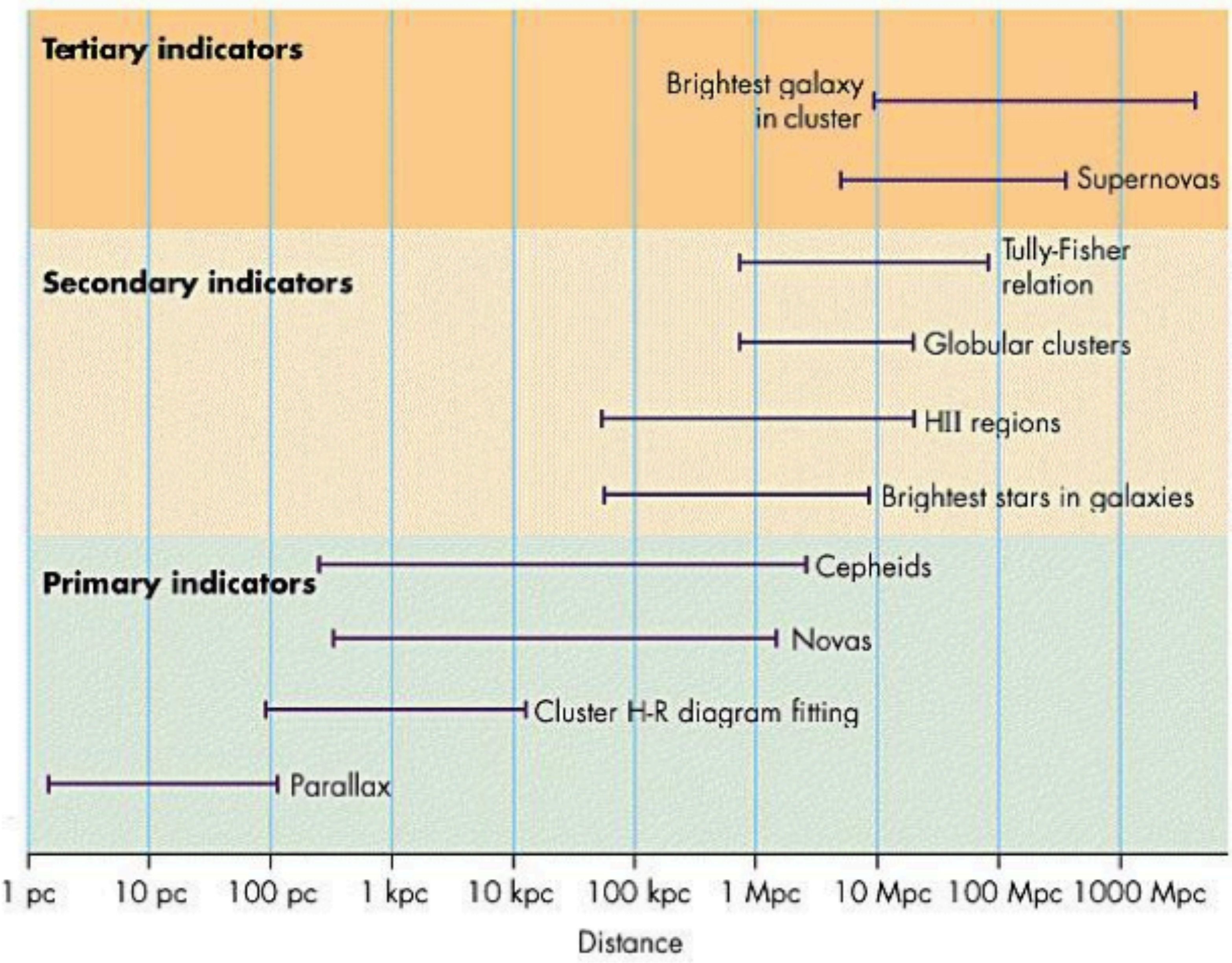
Hubble (1929)

Hubble Space Telescope (2000)

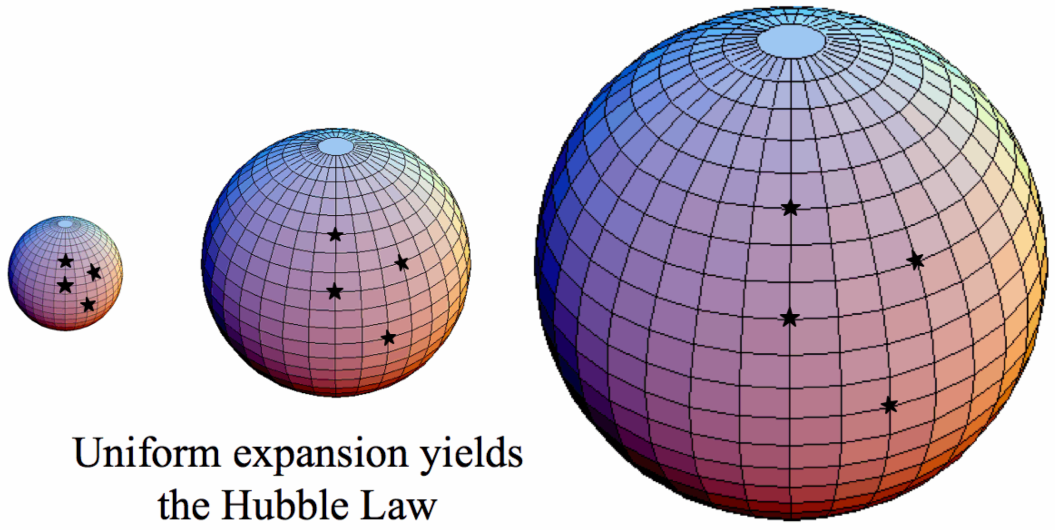
Freedman, etal

Courtesy of L.Amendola

# Distance indicators



# Step by step through history



Uniform expansion yields the Hubble Law

We observe Hubble law:

$v_B = Hd_B$
$v_A = Hd_A$

By vector addition,

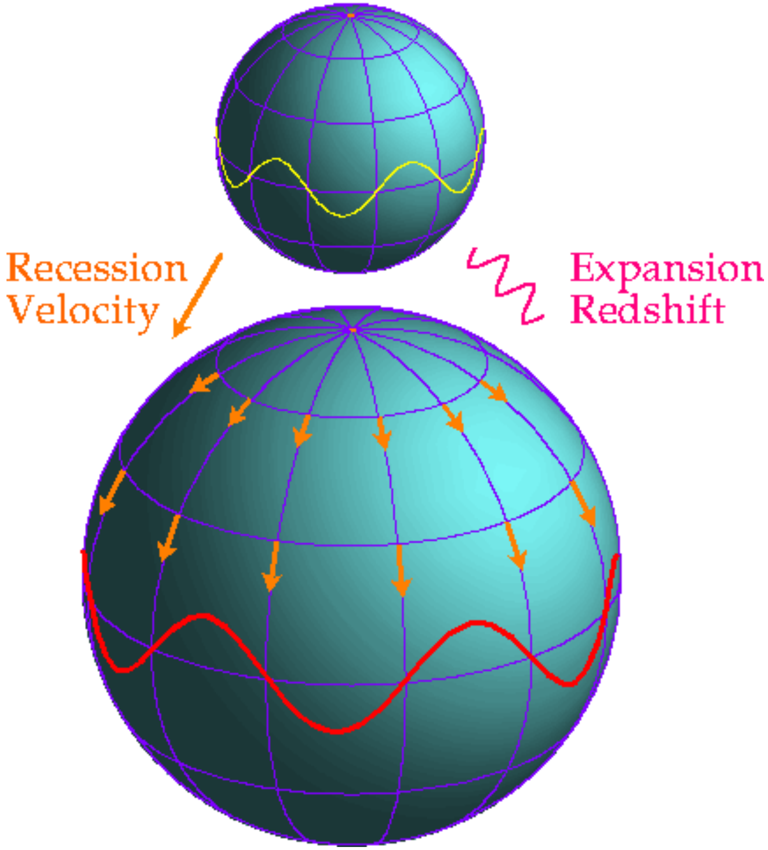
$$
\begin{aligned}
v_{BA} &= v_B - v_A \\
&= H(d_B - d_A) \\
&= Hd_{BA}
\end{aligned}
$$

Courtesy of L.Amendola

# Scale factor

One degree of freedom, function of time, that describes the background universe and how it expands.

# Scale factor

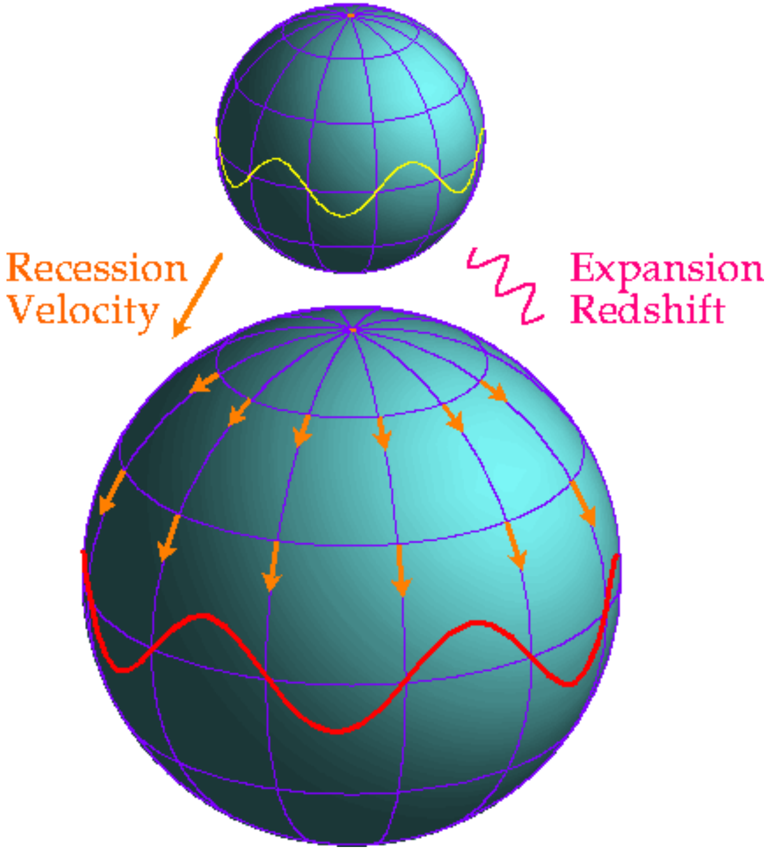


$a(t_1)$

$a(t_2)$

Galaxies are on average at rest. They are gravitationally bound and do not expand. Space in between them expands.

# Scale factor and redshift



$a(t_1)$

$a(t_2)$

$$1+z=\frac{a(t_0)}{a(t)}$$

redshift

Galaxies are on average at rest. They are gravitationally bound and do not expand. Space in between them expands.

# Cosmological redshift

$$1 + z = \frac{a(t_0)}{a(t)}$$

scale factor today

Redshift, all wavelengths are stretched with the expansion, shifted towards the ‘redder’ part of the spectrum (higher wavelength, proportional to the scale factor).

This is not the velocity at which galaxies move (peculiar velocities). Galaxies are on average at rest. They are gravitationally bound and do not expand. Space in between them expands.

# Expansion and Hubble parameter

Expansion rate:

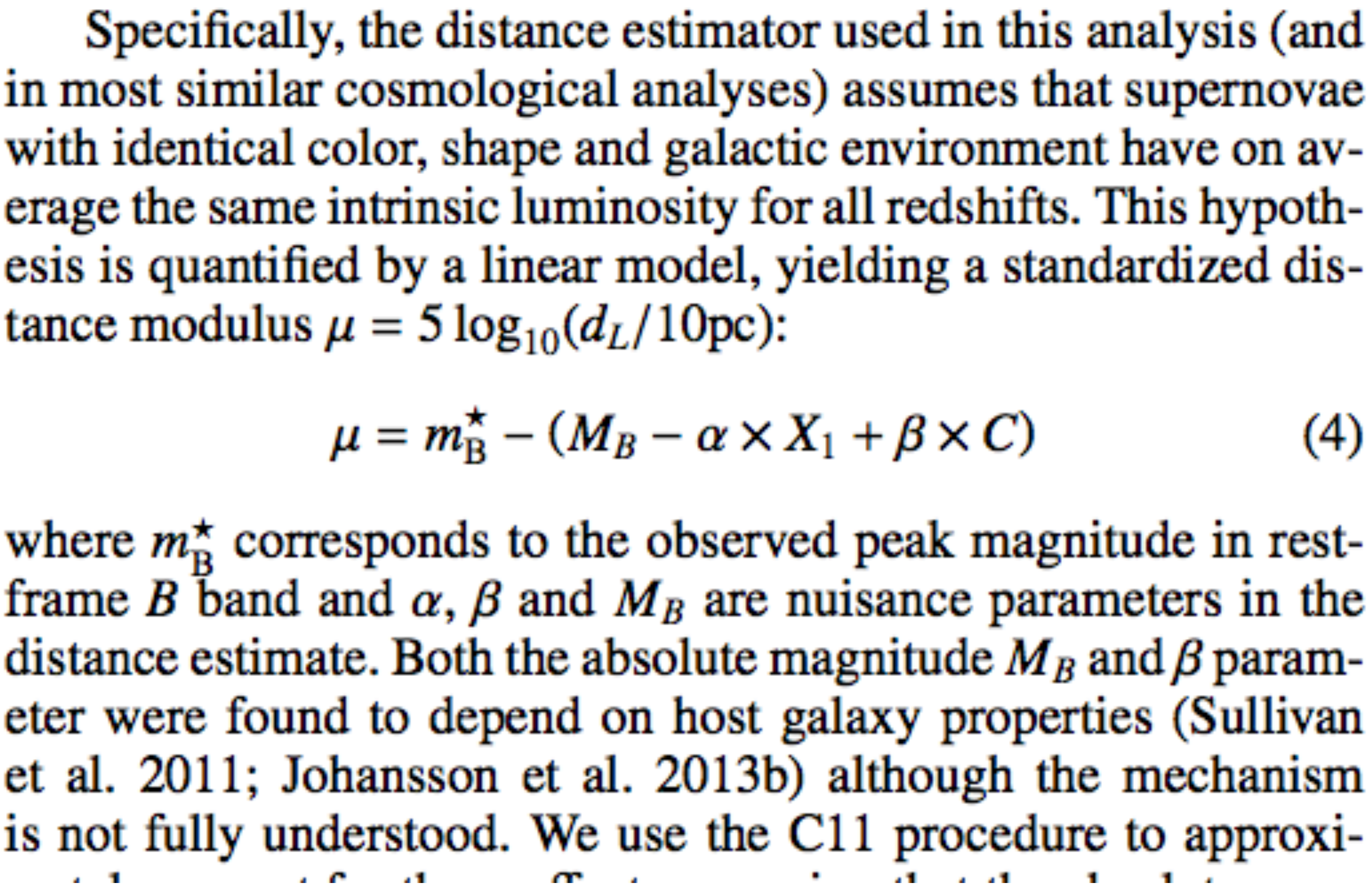
$$H = \frac{a_t}{a}$$

← Derivative of the scale factor with respect to time

The expansion is related to the density content of the Universe and to the geometry of space time via the Friedmann equations (as we will see later).

# Present measurements from SNae

Still using the Leavitt/Hubble relation between magnitude and distance, with a few adjustments.



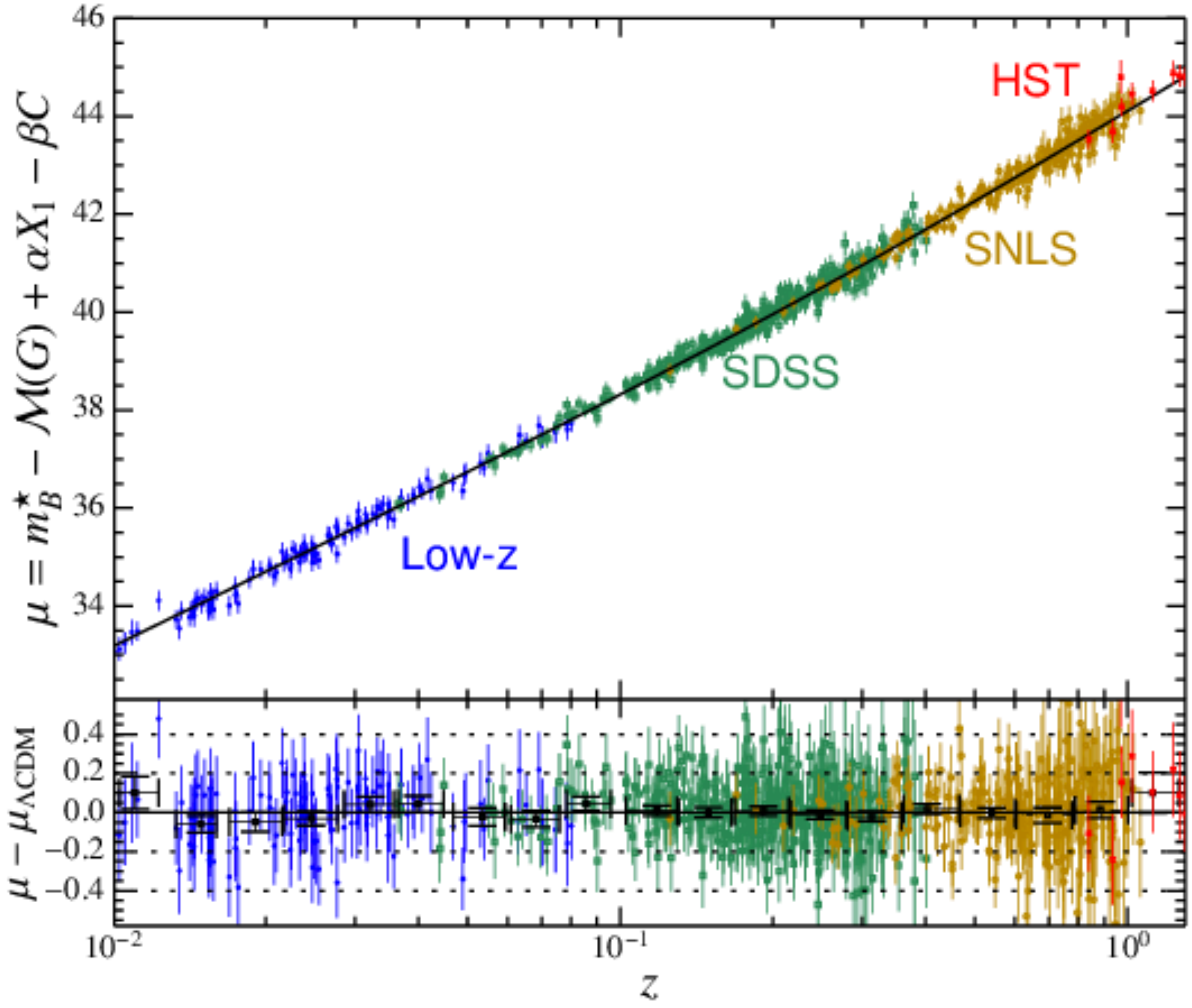
Specifically, the distance estimator used in this analysis (and in most similar cosmological analyses) assumes that supernovae with identical color, shape and galactic environment have on average the same intrinsic luminosity for all redshifts. This hypothesis is quantified by a linear model, yielding a standardized distance modulus $\mu = 5\log_{10}(d_L/10\mathrm{pc})$:

$$\mu = m_{\mathrm{B}}^{\star} - (M_B - \alpha \times X_1 + \beta \times C) \tag{4}$$

where $m_{\mathrm{B}}^{\star}$ corresponds to the observed peak magnitude in rest-frame $B$ band and $\alpha$, $\beta$ and $M_B$ are nuisance parameters in the distance estimate. Both the absolute magnitude $M_B$ and $\beta$ parameter were found to depend on host galaxy properties (Sullivan et al. 2011; Johansson et al. 2013b) although the mechanism is not fully understood. We use the C11 procedure to approxi-

Betoule et al. 2014

# Present measurements from SNae



Hubble (Leavitt) diagramme, JLA analysis

Betoule et al. 2014

# Back in time

Back in time, the scale factor is smaller, the density and temperature increases as the content in it is compressed

Singularity at a = 0, about 13 billion years ago

Peter Arnold, Inc./Alamy

# Overview of standard cosmology

Cosmological principle, isotropy and homogeneity

Distances: Hubble law and expansion of the Universe

Abundances of light elements

Background Cosmology in General Relativity

Supernovae and Cosmic acceleration

Cosmic Microwave Background

Structure formation

The Dark Universe

# Big Bang Nucleosynthesis

Using General Relativity, assuming a homogeneous and isotropic universe and the standard model of nuclear and particle physics, we can predict what should happen during the first three minutes of cosmic evolution.

What we observe are the relic abundance of the elements today.

BBN is one of the best established signatures of the early universe
and of the Big Bang hypothesis.

BBN describes the origin of light elements (helium, deuterium, lithium)

# Big Bang Nucleosynthesis

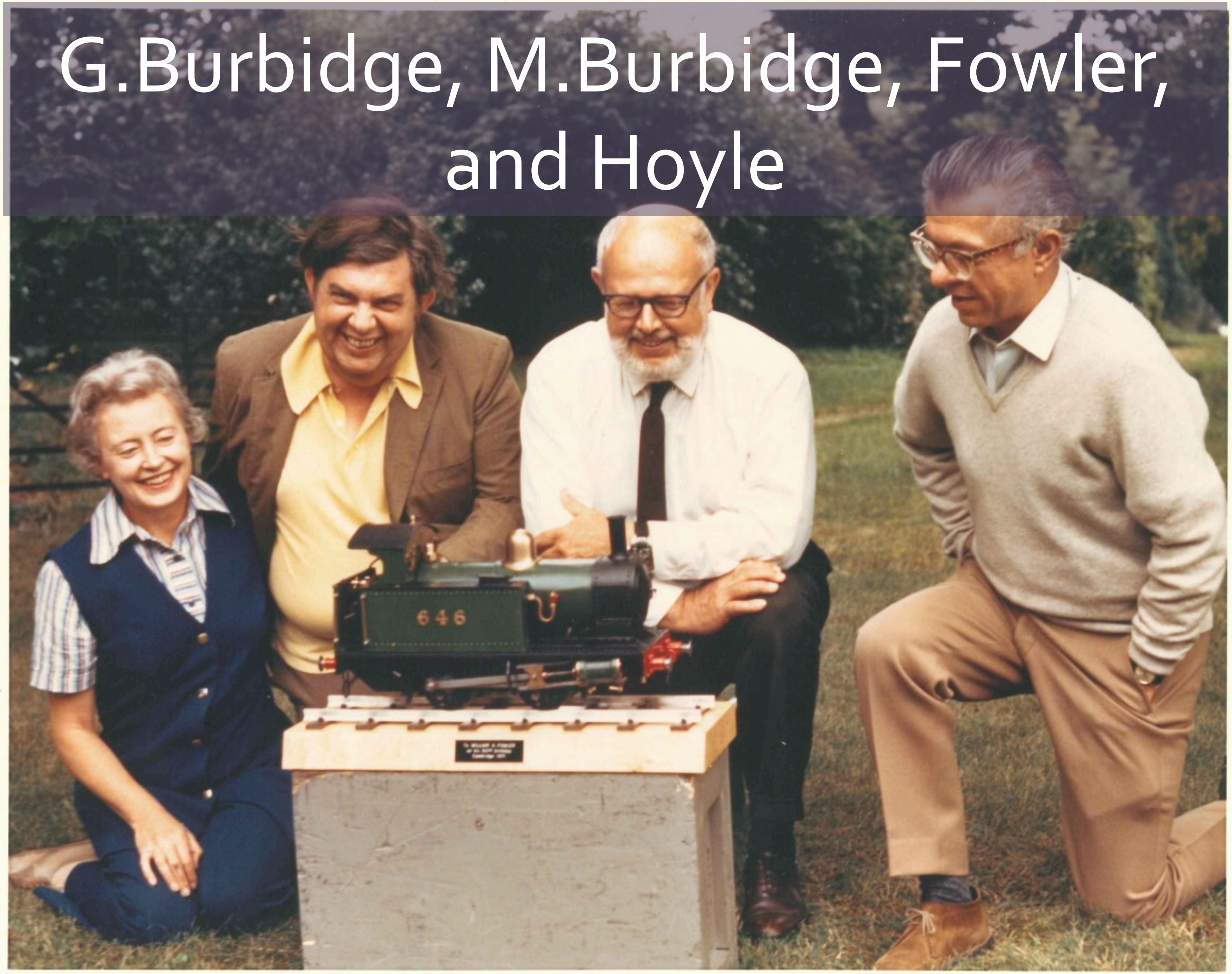
In the 1950's and 60's the predominant theory regarding the formation of the chemical elements in the Universe was due to the work of G.Burbidge, M.Burbidge, Fowler, and Hoyle. The BBFH theory postulated that all the elements were produced either in stellar interiors or during supernova explosions.

Problem: BBFH hypothesis could not by itself adequately explain the observed abundances of helium and deuterium in the Universe.

- It was estimated that only a small amount of matter found in the Universe should consist of helium if stellar nuclear reactions were its only source of production, while it is observed that about 25% of the Universe's total (baryonic) matter consists of helium
- Deuterium cannot be produced in stellar interiors but it is rather destroyed inside of stars.

Ref: M.White

# G.Burbidge, M.Burbidge, Fowler, and Hoyle



Re

# Big Bang Nucleosynthesis

Light elements were produced in the first few minutes of the Big Bang, while elements heavier than helium have their origins in the interiors of stars which formed much later in the history of the Universe

George Gamow

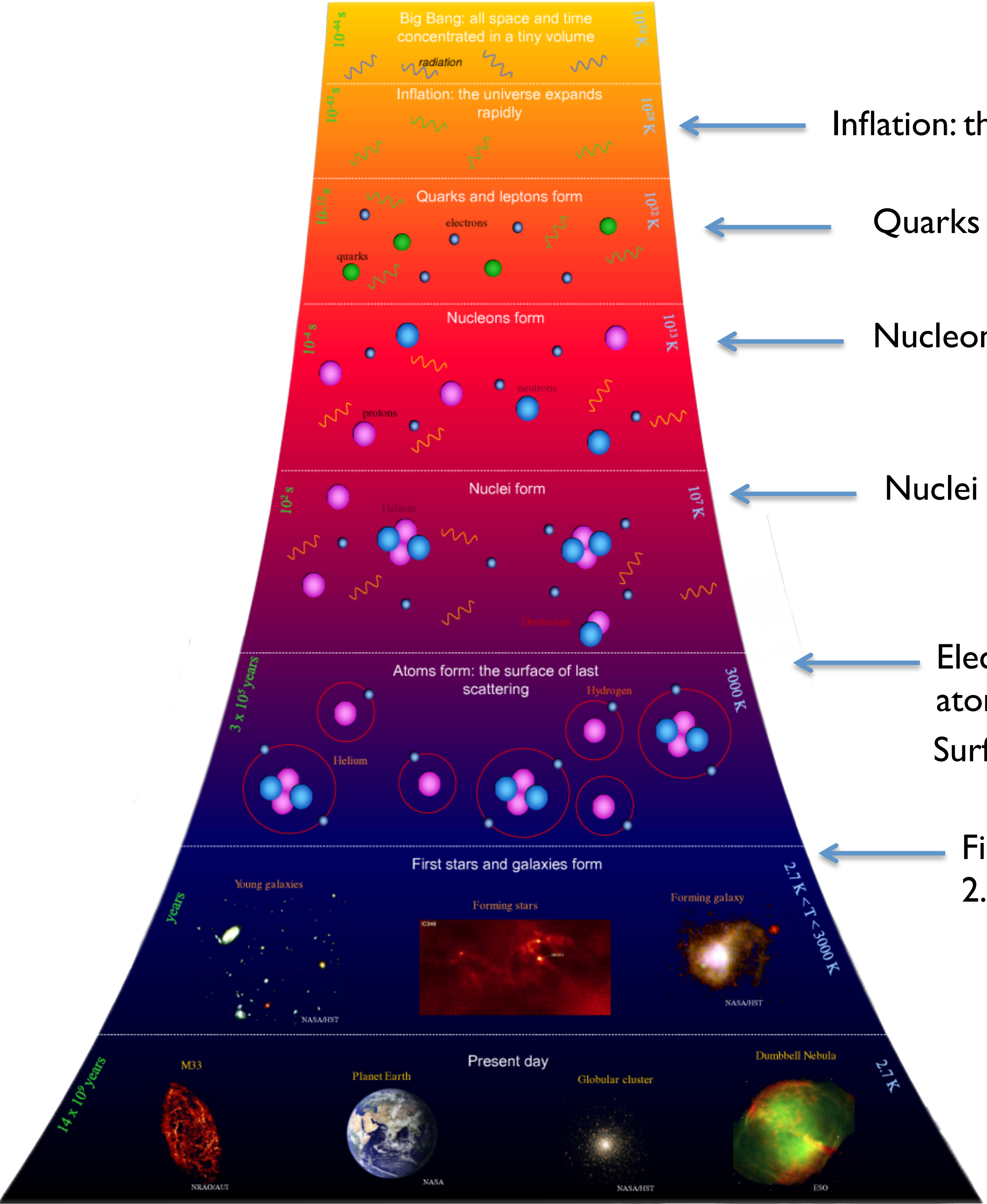
Ref: M.White

# A very hot early universe

When Temperature (T) was very high, there were no neutral atoms or bound nuclei: radiation was so much to ensure that they would be immediately destroyed by a high energy photon.

The Universe cooled down with the expansion: as T dropped below the binding energies of typical nuclei, light elements began to form.

Knowing the conditions of the early universe and the nuclear cross sections, one can calculate the expected primordial abundance of the elements.



Inflation: the Universe expands rapidly

Quarks and leptons form: $10^{15}$ K

Nucleons (protons, neutrons) form: $10^{13}$ K

Nuclei form $10^{7}$ K (of Helium and Deuterium)

Electrons join the nuclei and
atoms (Hydrogen, Deuterium, Helium) form.
Surface of last scattering. 3000 K, 380,000 yrs

First stars and galaxies form:
2.7 < T < 3000 K, 200 X $10^{6}$ yrs

Present day: 2.7 K, 13.6 X $10^{9}$ yrs

# Relating age, temperature and energy

$$T(t) \approx 10^{10} K \left(\frac{t}{1s}\right)^{-1/2}$$

$$k_B T(t) \approx 1 MeV \left(\frac{t}{1s}\right)^{-1/2}$$

# t < 1 s, T > 1 MeV ($10^{10}$K)

Particles: photons, neutrinos (and protons, neutrons, electrons with an abundance lower by a factor $10^{10}$ seen before).

Weak interactions can convert protons into neutrons and viceversa

In thermal equilibrium:

$$n \underset{\longleftarrow}{\longrightarrow} p + e + \nu$$

$$\frac{n_n}{n_p} = e^{-Q/kT}, \quad Q \equiv (m_n - m_p)c^2 = 1.2934\,\mathrm{MeV}\,.$$

At high T >> Q, there is the same number of neutrons and protons.
As T drops, Q/kT >>1, the interaction rate decreases and there are fewer neutrons (protons don't convert back). The neutron to proton ratio freezes in ($\Gamma/H < 1$) (the rate is smaller than the age of the universe) at $kT \approx 0.7$ MeV and t ≈ 3s at a value of:

$$\frac{n_n}{n_p} \approx e^{-1.2934/0.7} \approx 1/6.$$

# Baryon to photons

Photons are instead in thermal equilibrium (via Thomson scattering on free electrons) until much later than BBN.

Before decoupling, they follow a blackbody distribution.

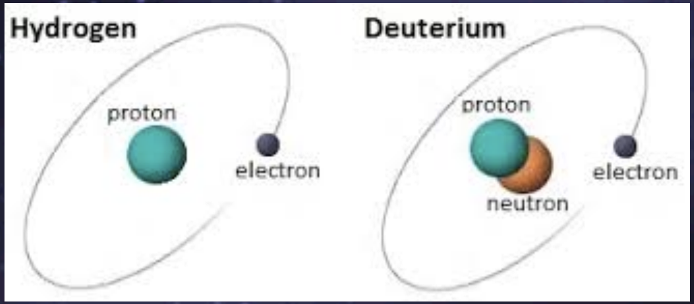
$$\eta \equiv n_b/n_\gamma = 5.4 \times 10^{-10} \left(\frac{\Omega_b h^2}{0.02}\right)$$

The photon density is 413 $\text{cm}^{-3}$
There is one baryon (proton or neutron) for every billion CMB photons.

# t ≈ 2 min, T ≈ 0.1 MeV ($10^9$K)

Deuterium (1 neutron + 1 proton) is the first to form

$$(n+p \rightarrow \mathrm{D}+\gamma).$$

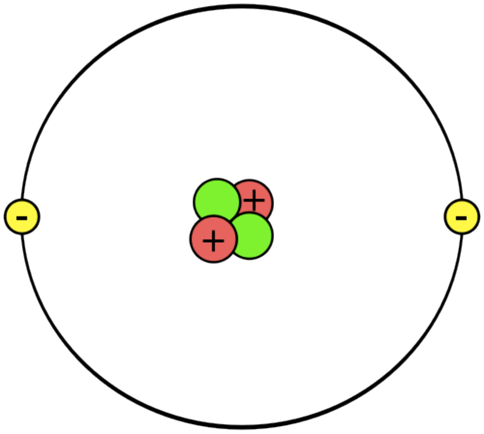


Deuterium has a binding energy of $B_D$ = 2.22 MeV but its synthesis starts later.
At 0.1 MeV the process is very fast and deuterium is quickly formed.

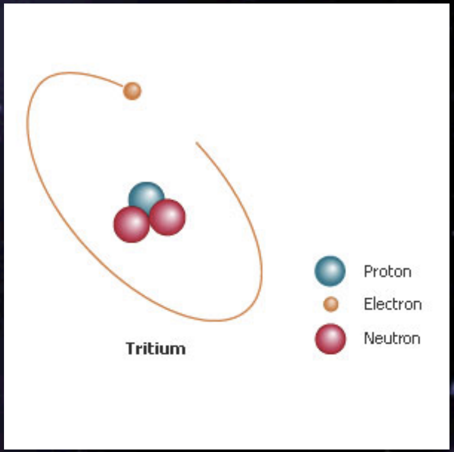
The baryon to photon ratio is very small: the photons in the tail of the blackbody distribution can still dissociate deuterium even when kT is below $B_D$.

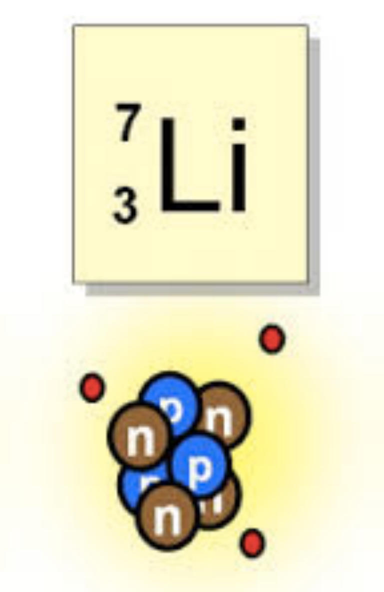
n/p ≈ 1/7 when deuterium forms

# t ≈ 2 min, T ≈ 0.1 MeV ($10^9$K)



Most of the deuterium then collides with other protons and neutrons to produce helium and a small amount of tritium (one proton and two neutrons). Lithium 7 could also arise from one tritium and two deuterium nuclei.





# Big Bang Nucleosynthesis

The Big Bang Nucleosynthesis theory predicts that roughly 24±1% of the baryonic mass of the Universe consists of $He^4$, with the rest made of mainly Hydrogen.
Small amounts: 0.01% of deuterium and even smaller quantities of lithium.

The important point is that the prediction depends critically on the density of baryons (i.e. neutrons and protons) at the time of nucleosynthesis.

Ref: M.White

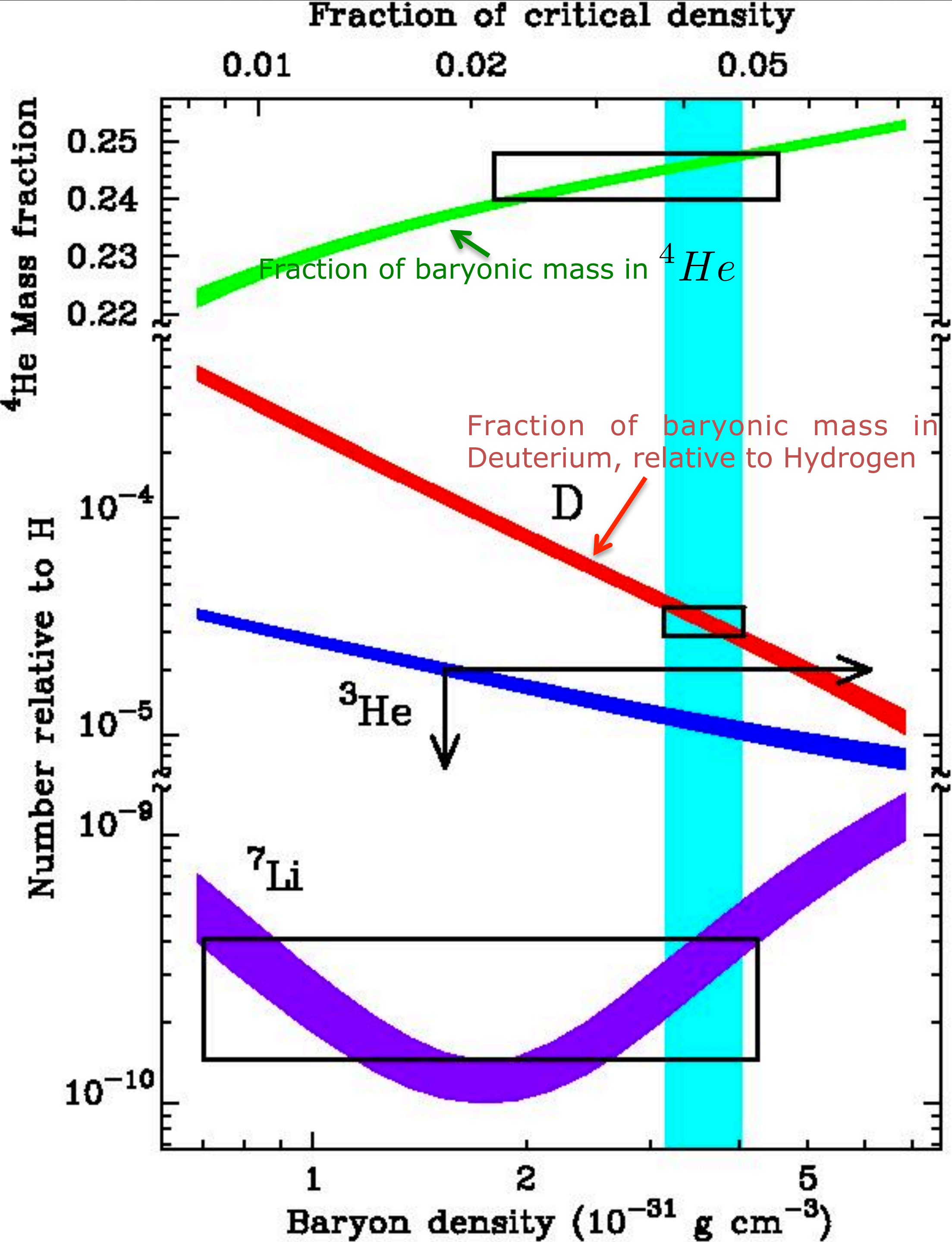
# BBN

Constraints on mass fraction as a function of the baryon density from BBN.

Predictions for four light elements in a range of 10 orders of magnitude in mass.

Vertical band is fixed mainly by measurements of primordial deuterium (QSO absorption lines): the same value of baryon density (few per cent of the critical one) matches all observations.

Boxes are the observations and overlap very well with the theoretical expectations. On $^3$He there is only an upper limit.



Fraction of baryonic mass in $^4He$

Fraction of baryonic mass in Deuterium, relative to Hydrogen

# Big Bang Nucleosynthesis

Heavier nuclei than $^7$Li are produced in stars, via reactions that require higher temperature and density. Ex.:

$$^4He + ^4He + ^4He \rightarrow ^{12}C^*$$

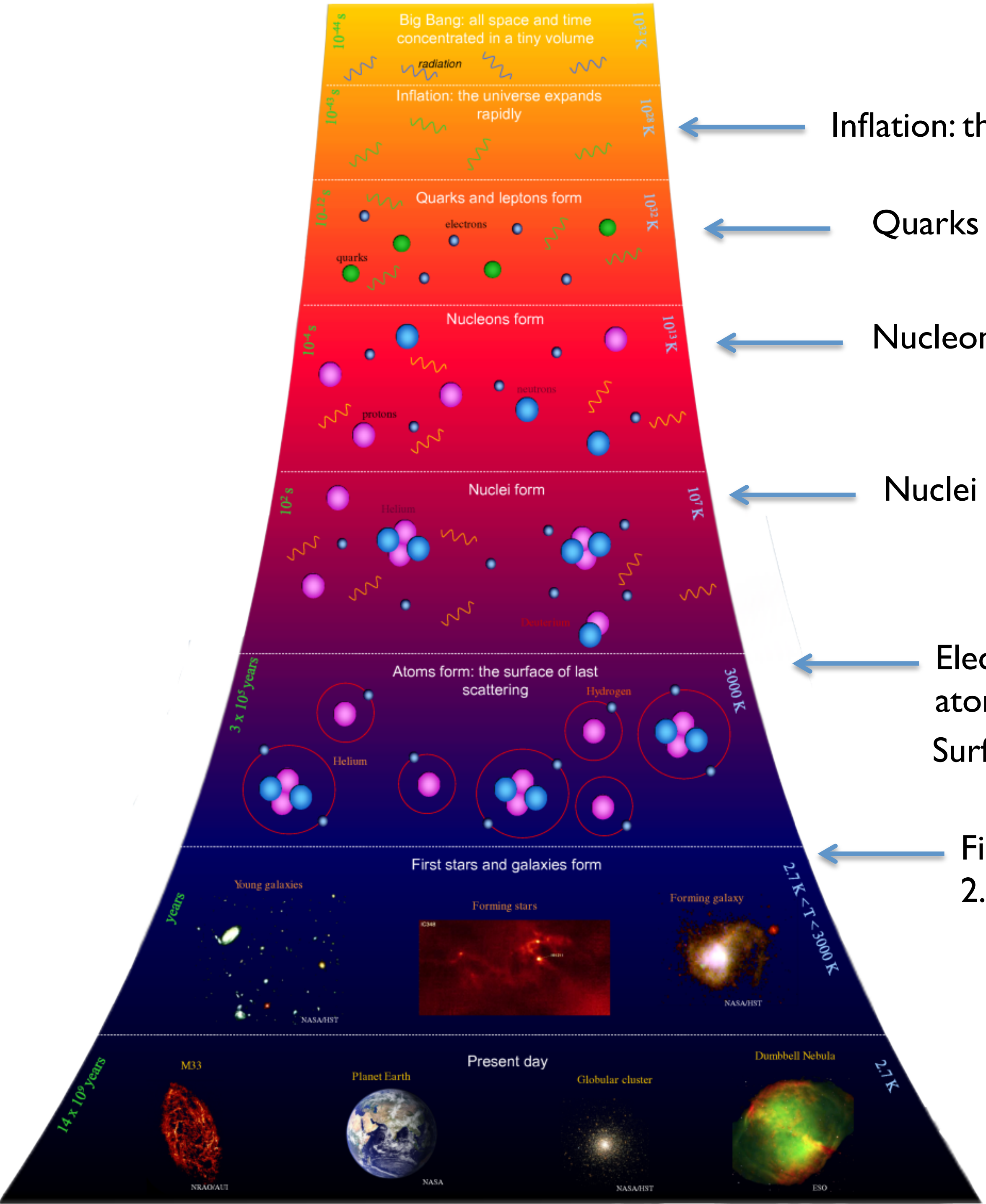
# Big Bang Nucleosynthesis and CMB

The Cosmic Microwave Background (CMB) has also been used to get a completely independent measurement of the baryon density:

$$\Omega_b h^2 = 0.022 \pm 0.001$$

In very good agreement with other determinations.

Ref: M.White



Inflation: the Universe expands rapidly

Quarks and leptons form: $10^{15}$ K

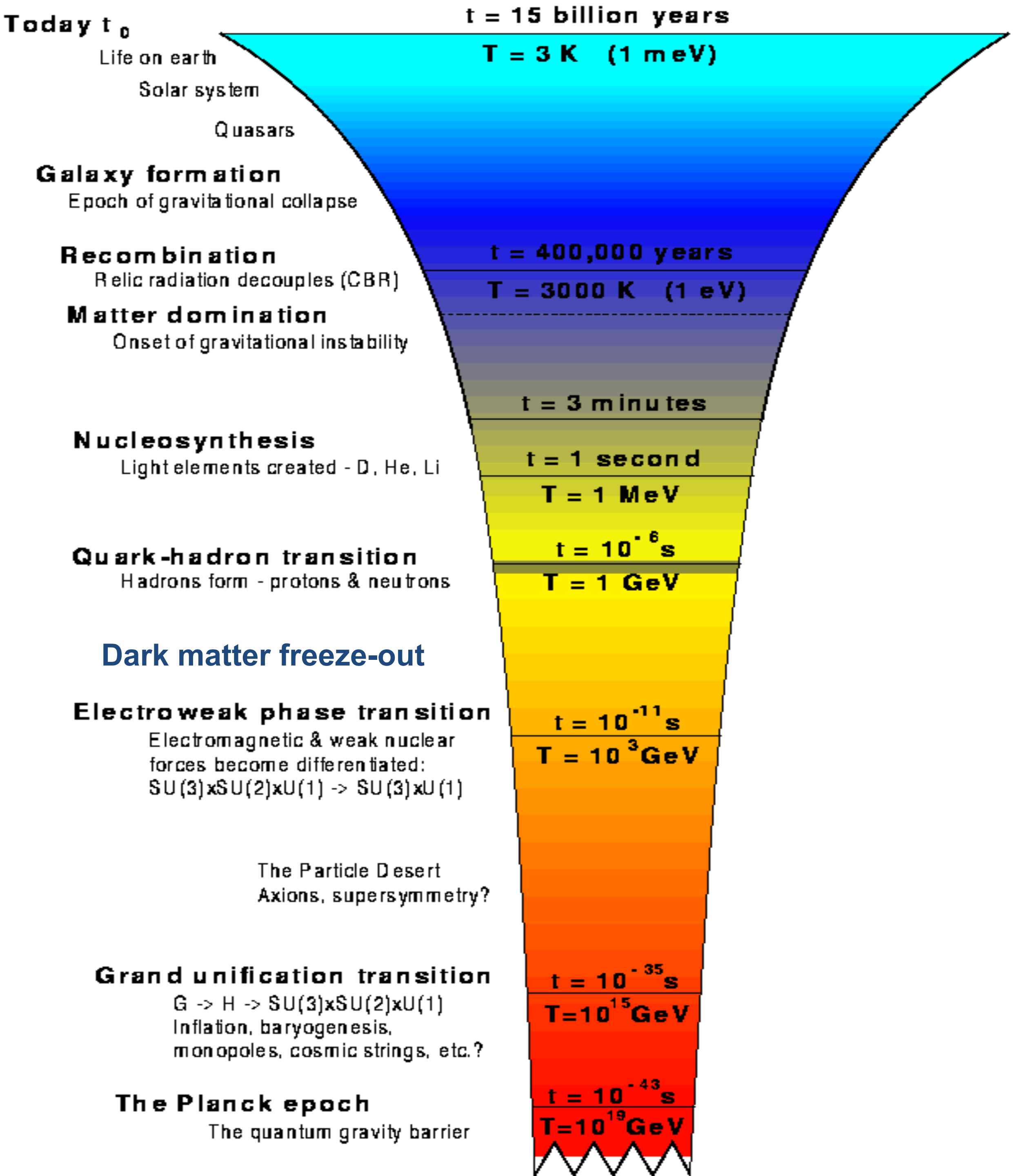
Nucleons (protons, neutrons) form: $10^{13}$ K

Nuclei form $10^{7}$ K (of Helium and Deuterium)

Electrons join the nuclei and
atoms (Hydrogen, Deuterium, Helium) form.
Surface of last scattering. 3000 K

First stars and galaxies form:
2.7 < T < 3000 K

Present day: 2.7 K



**Looking for signatures of the early universe, relics of the physics at early times, observables that required hot temperature and densities to be produced**

# Overview of standard cosmology

Cosmological principle, isotropy and homogeneity

Distances: Hubble law and expansion of the Universe

Abundances of light elements

Background Cosmology in General Relativity

Supernovae and Cosmic acceleration

Cosmic Microwave Background

Structure formation

The Dark Universe